# The Marin Countywide Plan

## Environmental Hazards Element Technical Report #3
## Seismic Hazards in Marin



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## EXECUTIVE SUMMARY

The Marin Countywide Plan Environmental Hazards Element, adopted in 1977, must be updated to include new information and more recent State of California requirements for hazards planning. This technical report examines existing seismic and geologic hazard conditions and proposes amendments to the Countywide Plan Environmental Hazards Element.

A large portion of the land in Marin County is subject to a variety of natural and man-made hazards. In order to protect the public, the Countywide Plan should identify areas where hazards to life and property occur and the Plan should set forth protective measures to reduce risk. These factors will then be considered in the type, location, design, and density or intensity of development in the County. Long term costs to the County, such as maintenance, liability exposure, and emergency services, are potentially greater where high hazards exist. The extent of the hazard depends on local conditions, since most hazards are confined to a particular area or site. These areas are generally as follows:

> *Upland Areas*: Upland areas are subject to geologic and seismic hazards, but the risk is variable and determined by underlying geologic materials.
>
> *Valley Floors*: Valley floor areas may be considered relatively stable from the standpoint of slope stability but may be hazardous if located in the path of debris flow or other types of landslides. Seismic hazards include ground shaking and liquefaction in water-saturated alluvial deposits.
>
> *Baylands*: Baylands consisting of artificial fill over bay mud are hazardous from both a seismic and geotechnical standpoint. Ground shaking during an earthquake is greatly intensified on bay mud and thus more damaging than on bedrock. Additionally, an earthquake may trigger liquefaction if sand, silt, or gravel is present, and lateral spreading, lurching and differential settlement of soft, saturated clays such as San Francisco Bay Mud. Even without a seismic event, areas within historic baylands are subject to subsidence and differential settlement over long periods of time depending on the thickness of the underlying bay mud. Differential settlement results in cracking of sidewalks and pavement as well as breaking of sewer lines and other infrastructure, creating future maintenance and repair problems. If predictions of a rise in sea level are accurate, then flood hazards to low-lying areas can be expected to increase, especially in combination with ground subsidence.

The safety goals of the Countywide Plan are aimed at reducing death, injuries, damage to property and the economic and social dislocation resulting from geologic hazards and other public health and safety concerns. The intent is not to remove all risks associated with each specific type of hazard, but to reduce risks to life and property and to make informed decisions about development near these hazards. Implementation will occur through the County's Zoning Ordinance and review of specific development proposals. In addition, Marin County government agencies engage in a number of geologic and seismic safety protection measures. The Marin County Department of Emergency Services is preparing a County Multi-Hazard Plan which outlines actions to insure effective disaster response. Continued coordination among various departments and other local and state agencies are part of an effective emergency response plan.

The major modifications to the Environmental Hazards Element proposed in this technical report focus on the following:

1. Information on seismic hazards in existing buildings and a new program, Program 2.3a, implementing the requirements of SB 547 described under Section III.

2. Policy 3.1 requires that projects not be endangered by or contribute to the hazardous conditions on the site or on adjoining properties. This policy also requires consideration of aesthetic impacts in designing geologic and seismic hazard mitigation.

3. Policy 6.1 implements existing practices requiring evaluation of hazards in slope stability zone 1 and 2 (in addition to 3 and 4) where the potential for landslides exists.

## I. PURPOSE

The current Environmental Hazards Element, adopted in 1977, has not been revised to include recent legislation or information primarily related to seismic safety in existing buildings. This technical report reviews current legal authority for seismic and geologic hazard planning, seismic and geologic hazards in Marin County, and current seismic and geologic hazard protection measures. The report suggests revisions to the Countywide Plan Environmental Hazards Element which will improve conformance with existing environmental and programmatic conditions.

## II. AUTHORITY FOR SEISMIC AND GEOLOGIC HAZARD PLANNING

The authority under California law for seismic and geologic hazards planning in city and county general plans is covered in the California Government Code. Policies and programs related to these safety issues have been required as part of general plans since 1971.

The San Fernando earthquake of February, 1971, which claimed 64 lives and resulted in over $500 million in property damage, and the devastating wildland fires in September and October of 1970 were largely responsible for prompting the Legislature to pass this requirement. The Government Code requires cities and counties to protect the public against unreasonable risk due to seismic and geologic hazards by requiring the general plan include the following (Government Code 65302 (f)):

> A safety element for the protection of the community from any unreasonable risks associated with the effects of seismically induced surface rupture, ground shaking, ground failure, tsunami, seiche, and dam failure; slope instability leading to mudslides and landslides, subsidence and other geologic hazards known to the legislative body; flooding; and wildland urban fires. The safety element shall include mapping of known seismic and other geologic hazards. It shall also address evacuation routes, peakload water supply requirements, and minimum road widths and clearances around structures, as those items relate to identified fire and geologic hazards.
>
> To the extent that a county's safety element is sufficiently detailed and contains appropriate policies and programs for adoption by a city, a city may adopt that portion of the county's safety element that pertains to the city's planning area in satisfaction of the requirement imposed by this subdivision. Each county and city shall submit to the Division of Mines and Geology of the Department of Conservation one copy of the safety element and any technical studies used for developing the safety element.

To assist local governments in meeting these responsibilities, the Government Code (65040.2) directs the Office of Planning and Research (OPR) to adopt and periodically revise guidelines for the preparation and content of local general plans. The guidelines establish standards for assessing the adequacy of local general plans. Some of the issues identified in the guidelines include:

> The effects of seismically induced surface rupture, ground shaking, ground failure, tsunami, seiche, and dam failure;
>
> The effects of slope instability leading other geologic hazards known to the legislative body;
>
> Mapping of known seismic and other geologic hazards;
>
> Assessment of the potential for surface rupture;
>
> Assessment of the potential for ground shaking;
>
> Assessment of the potential for ground failure, including an evaluation of the potential for seismically induced landslide, mudslide, liquefaction and soils compaction;
>
> Assessment of the potential for tsunamis and seiches and inundation from seismically induced dam failure (this issue is covered in Environmental Hazards Technical Report # 1, <u>Flood Hazards</u>);
>
> Assessment of slope stability;
>
> Assessment of the potential for land subsidence; and
>
> Assessment of the adequacy of existing emergency preparedness and evacuation plans to deal with the identified hazards.

Seismic hazards, in particular, have been the focus of legislative attention. California has recently been moving toward more comprehensive seismic policy development. In 1985, the Legislature enacted the California Earthquake Hazards Reduction Act, a landmark in seismic policy-making, establishing a system of comprehensive and continuous seismic hazards planning. It included a goal of the achievement of significant earthquake-hazard reduction by the year 2000. The new law will further earthquake safety by setting up a five-year program in six major areas: (1) existing development; (2) emergency preparedness and response; (3) new development; (4) long-term recovery; (5) education; and (6) research and application.

The five-year program prepared in 1986 represents the State's first attempt to develop and implement a comprehensive earthquake safety plan. The California Seismic Safety Commission was chosen to lead the program, working with other agencies representing a wide range of concerns. Local governments have major responsibilities in helping to maximize earthquake safety. The future safety of a community can be shaped by the way local government handles such functions as land use control, code review and enforcement, inspection of building construction, emergency management, and disaster planning.

Other legislation also relates to the scope and content of local general plans. The most prominent are the Alquist-Priolo Special Studies Zones Act and SB 547 (codified in Section 8876 of the Government Code). The Alquist-Priolo Special Studies Zones Act went into effect in 1973. The purpose of the Act is to prohibit the location of most structures for human occupancy from the traces of active faults and to mitigate thereby the hazard of fault rupture. The Act applies to the San Andreas Fault in Marin County.

SB 547 (Government Code 8876) covers reduction of hazards in existing buildings. The law requires counties and cities to conduct inventories of all unreinforced masonry buildings in their jurisdiction. Once the inventories are complete, the local governments are required to develop mitigation programs for these buildings. Inventories and mitigation programs must be completed by 1990. The law also authorizes local building departments to establish a schedule of fees to recover the costs of identifying potentially hazardous buildings and carrying out other requirements of the law.

The County has one unreinforced masonry building, the Grandi Building in Point Reyes Station. As many as 240 such structures may be located within city limits in Marin.

## III. GEOLOGIC SETTING OF MARIN COUNTY

### A. OVERVIEW

Marin County is located in the coast range of California, which consists of an alternating series of parallel mountains and valleys located adjacent to the Pacific coast. The bedrock units that form the range have been disrupted by the intense folding, faulting, and crushing that occurred when the range was formed by the processes of plate tectonics. The theory of plate tectonics hypothesizes that the earth's surface consists of a rigid crust up to 40 miles and is broken up into a series of blocks referred to as plates. The plates move about the earth's surface over a fluid zone of molten rock beneath the earth's crust.

Millions of years ago, the Pacific Oceanic Plate, which was progressively moving towards the east, collided with the North American Continental Plate which was moving towards the west. This collision caused the less rigid Pacific Oceanic Plate to bend down beneath the North American Continental Plate in a process known as subduction. The continued colliding motion of the two plates caused portions of the Pacific Oceanic crust and marine settlements deposited on that crust to be scraped off and piled up onto the North American Continental Plate along the west coast of the United States.

The resulting chaotic jumble of bedrock units scraped off onto the North American Continental Plate is known as the "Franciscan assemblage." The Franciscan assemblage occupies much of the coast range province and most of Marin County. Subsequent development of a series of northwest-trending active fault zones has further contributed to the deformation of the coast range.

The San Andreas Fault is an active rupture between the Pacific Oceanic Plate and the North American Continental Plate. The "mainland" side of the San Andreas Fault in Marin County is a complex and disrupted assemblage of sedimentary, igneous, and metamorphic rock masses generally called the Franciscan Formation (KJF). The Franciscan Formation is widespread in the coast ranges. It originated during late Jurassic and Cretaceous periods (roughly between 150 million and 80 million years ago), as the North American plate was moving westward and overriding the crust of the earth beneath the Pacific Ocean. The Franciscan Formation is composed mostly of sandstone and mudstone that originated as sediments deposited in the ocean.

The most disrupted elements of the Franciscan Formation are called melange. Melange yields some of the most interesting landscape in the County. The weak, sheared matrix is seldom exposed, for it is easily eroded away, leaving an uneven surface decorated with scattered knolls, blocks, and monuments of the various unsheared and resistant rock masses that had been enclosed in it. Many of the prominent ridges, hills, and knolls in the County are made up of great, relatively coherent blocks and slabs of sandstone, volcanic rocks, or chert, up to many miles in dimensions, that resisted dismemberment during the great shearing deformations. Most of the valleys in Marin have been formed by erosion of weaker mudstone and melange matrix.

The final episode in the geologic development of eastern Marin County was the Pleistocene era ("Ice Age") with the formation of the depression of San Francisco Bay by downfaulting (downwarping) of the earth's crust. Immense quantities of water accumulated in the continental ice sheets and lowered sea level as much as 350 feet at times. The glacial maxima drained the Bay and led to great erosion by the Sacramento River passing through the resulting valley, and by increased effectiveness of tributary streams to cut steepsided valles, gorges, and ravines into the Marin uplands.

With the melting of most of the last ice sheets, beginning about 12,000 years ago, sea level gradually rose to its present level. Most of the clay and silt carried by river flood waters were deposited within the now quiet waters of the bay. Thus the old valley system has been partially buried by the soft organic silty clay called bay mud (Qal) that makes up our marshlands and mudflats.

The bedrock units on Point Reyes Peninsula, west of the San Andreas Fault, originated many miles to many hundreds of miles southeast of their present location, and have reached their present location by displacement along the fault. The Pacific Plate, including Point Reyes Peninsula, is continuing its intermittent northwesterly migration past Marin County at an average rate of 2 inches or more per year.

It was a sudden displacement of 15 to 20 feet along the San Andreas Fault that created the great "San Francisco" earthquake of 1906. Similar earthquakes must have occurred innumerable times in the past resulting from this relentless driving mechanism, and will no doubt occur in the future.

The oldest of the rock types of the peninsula are the granitic rocks (Gr) of Inverness Ridge and Point Reyes (about 80 million years old), with some small remnants of older metamorphic rocks embedded in them. The nearest granitic rocks on the east side of the San Andreas Fault with which the ones of Point Reyes Peninsula might be correlated are in the Tehachapi Range, in the southern "hook" of the Sierra Nevada, some 300 miles to the southeast.

During the course of their travels northward, the granitic and metamorphic rocks of the Point Reyes Peninsula region have been periodically and locally depressed below sea level, accumulating Cenozoic marine deposits of conglomerate, sandstone, siltstone, and mudstone in places. The coarse conglomerate (Ep) resting on granite at Point Reyes is of Paleocene age (about 60 million years ago). The Monterey Formation (Mm) of the area between Bolinas and Bear Valley, and the Drakes Bay Formation (Pm) of the central peninsula area, are shallow water marine deposits of late Miocene to early Pliocene age (7 to 26 million years ago). Similar sedimentary rocks do not occur on the east side of the San Andreas Fault in Marin County or vicinity. Table 1 shows Rock Units in Marin County in terms of geologic time (a glossary of terms used in this report appears in Appendix C).

## B. MAJOR GEOLOGIC FORMATIONS IN MARIN COUNTY

The major geologic units are discussed here in terms of those characteristics which are relevant to an understanding of natural hazards.

## Table 1. Rock Units in Marin County

| RELATIVE GEOLOGIC TIME | | | ATOMIC TIME (In millions of years) | ROCK UNITS IN MARIN COUNTY | |
|---|---|---|---|---|---|
| Era | Period | Epoch | | WEST OF THE SAN ANDREAS FAULT | EAST OF THE SAN ANDREAS FAULT |
| Cenozoic | Quaternary | Holocene | | Dune sand and Alluvium | Dune sand and Alluvium |
| | | Pleistocene | 1.8 | Marine terrace sediments | Marine terrace sediments |
| | Tertiary | Pliocene | 7 | Marine sedimentary rocks | Marine sedimentary rocks |
| | | Miocene | 26 | Marine sedimentary rocks | Volcanic rocks |
| | | Oligocene | 37-38 | | |
| | | Eocene | 53-54 | | |
| | | Paleocene | 65 | Marine sedimentary rocks | |
| Mesozoic | Cretaceous | Late<br>Early | 136 | Granitic rocks | Marine sedimentary rocks<br>Franciscan melange & Fran. Formation<br>Franciscan Volcanic rocks<br>Serpentine |
| | Jurassic | Late<br>Middle<br>Early | 190-195 | | |
| | Triassic | Late<br>Middle<br>Early | 225 | Rocks of these ages are not known to be present in Marin County | |
| Paleozoic | Permian | Late<br>Early | 280 | | |
| | Carboniferous Sys.: Pennsylvanian | Late<br>Middle<br>Early | | | |
| | Carboniferous Sys.: Mississippian | Late<br>Early | 345 | | |
| | Devonian | Late<br>Middle<br>Early | 395 | | |
| | Silurian | Late<br>Middle<br>Early | 430-440 | | |
| | Ordovician | Late<br>Middle<br>Early | 500 | | |
| | Cambrian | Late<br>Middle<br>Early | 570 | | |
| Precambrian | | | 3,600+ | | |

Greater detail of their origin and mineralogic composition can be found in the four technical reports and detailed legends to the large scale maps prepared for the County and cities by the California Division of Mines and Geology (copies of these technical reports and their accompanying maps are available at the Marin County Planning Department). Figure 1 shows the geology of Marin County.

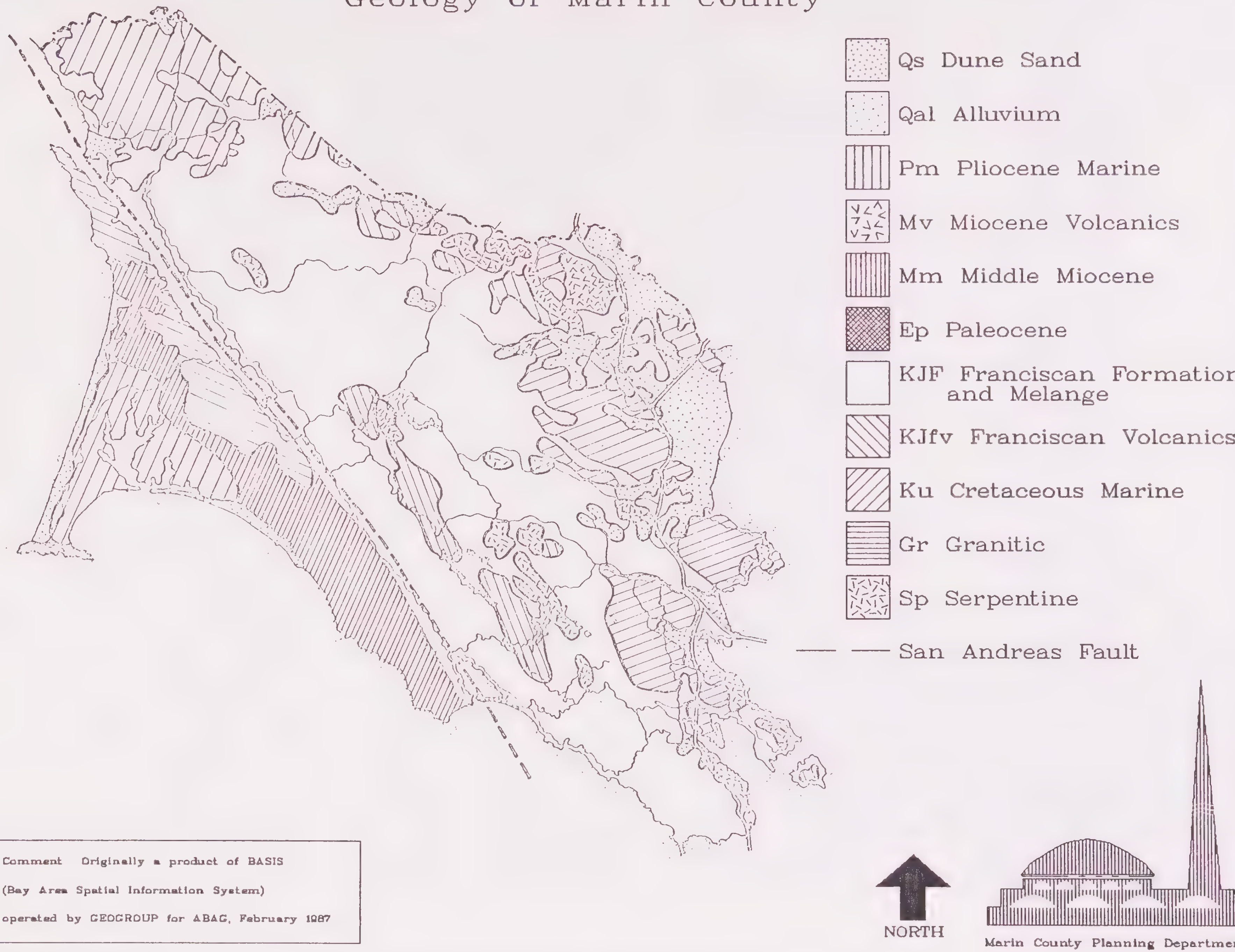
1. Franciscan Melange

The principal bedrock formation of the coast range, and of Marin (east of the San Andreas fault) is the Franciscan Formation. The Franciscan rocks consist predominantly of sandstone and shale formed from sand and mud washed into the ocean during late Mesozoic time, roughly between 90 million and 150 million years ago. In Marin County, the formation also contains large amounts of greenstone (altered from lava erupted under the sea), of radiolarian chert (a hard sedimentary rock of deep sea origin), or serpentine (an altered igneous rock related in origin to the mantle of the earth, beneath the crust), and scattered small but resistant masses of some unusual types of metamorphic rocks.

A large percentage of the Franciscan Formation in Marin County consists of Franciscan melange which occurs over about half of the eastern corridor. This is a disrupted assemblage of small and large masses of various hard rock types embedded in and separated from each other by more or less intensely sheared and crushed rock material. Melange terrain in Marin County is characterized in many places by the presence of scattered prominent outcrops or monument-like masses of hard rock projecting out of otherwise smooth grassy slopes. These hard or resistant masses ordinarily comprise an assortment of rock types, principally sandstone, greenstone, chert, serpentine, and glaucophone schists, that rarely show evidence of continuity between outcrops. Even when nearby outcrops are of a single rock type, such as sandstone, close examination most commonly reveals they are different from each other in texture, composition, and history.

Serpentine commonly occurs as extensive masses in melange. The presence of this waxy green rock in the Franciscan should strongly suggest the presence of the melange. Serpentine is an unusual rock type that originated below the crust of the earth; therefore, its presence at the surface supports the concept that the soft, sheared matrix of the melange represents a zone of great disruption. Although it is almost everywhere more or less thoroughly sheared in such settings, the serpentine tends to be a relatively stable material compared to the melange matrix that underlies or surrounds it and that occasionally undermines it by landsliding.

# Geology of Marin County



## Figure 2. Geologic Units of Marin County

### West of San Andreas Fault

| Period | Geologic Unit | |
|---|---|---|
| Quartenary | Qs | Beach Deposits |
| | Qa | Alluvium |
| | Qm | Bay Mud |
| | Qoa | Older Alluvium |
| | Qt | Terrace Deposits |
| Tertiary | QTmc | Merced Formation |
| | Tm | Monterey Shale |
| | Tl | Laird Sandstone |
| Mesozoic Cretaceous | Kgr | Granitic Rock |
| Paleozoic | Pms | Metamorphosed Sedimentary Rock |

### East of San Andreas Fault

| Period | Geologic Unit | | |
|---|---|---|---|
| Quartenary | Qaf | Artificial Fill | |
| | Qm | Bay Mud | |
| | Qa | Alluvium | |
| | Qc | Colluvium | |
| | Qs | Beach Deposits | |
| | Qoa | Older Alluvium | |
| | Qt | Terrace Deposits | |
| | Qmi | Millerton Formation | |
| Tertiary | Tv | Volcanic rocks, undifferentiated | |
| | Ts | Sedimentary Rocks, | |
| | Ks | Sandstone and shale | |
| | (Kjs) | ss - | sandstone |
| | | sh - | sandstone and shale |
| | | cg - | conglomerate |
| | Kn | Novato Conglomerate | |
| | KJg | Basaltic Volcanic Rocks | |
| | KJch | Chert | |
| | KJsch | Semi-schist, phyllite and schist | |
| Cretaceous | fm | Franciscan Melange | |
| | | ss - | sandstone and shale |
| | | ssh - | sandstone and shale |
| | | cg - | conglomerate |
| | | ch - | chert |
| | | gs - | greenstone |
| | | sch - | metamorphic rocks |
| | | am - | amphibolite |
| | | sp - | serpentine |
| | | sc - | silica-carbonate rock |

Because of the sharp differences in inherent strength characteristics of the various components of the melange, areas underlain by this type of material exhibit highly erratic slope stability characteristics. The crushed and intensely sheared melange is not only inherently weak in most places, but commonly it also weathers to yield a highly expansive clay-rich soil. Moderately steep slopes underlain by such material often exhibit evidence of slow downhill creep or debris flow landslides. As a result of the relative instability and erodibility of the melange, wide zones tend to form a disrupted topography.

Bold outcrops of hard, resistant rock masses and hummocks of soil-covered and more easily weathered sandstone and shale are separated by subdued swales that are the result of differential erosion and downslope migration of the weak melange and its soil cover.

The unsheared masses of coherent rock enclosed within the melange tend to have high strength. Where imbedded and not influenced by near-surface downslope movement, these masses also manifest high slope stability. Such masses commonly act as buttresses at the bottoms of slopes to support weak melange upslope from them -- an important factor to be recognized before such buttresses are removed in notching the base of slopes for house sites or road construction.

2. Semi-Schist and Related Metamorphic Rocks

The oldest rocks in eastern Marin County are the semi-schists: phyllites, metacherts, and metavolcanic rocks that underlie parts of the Novato, Terra Linda and Tiburon Peninsula areas. These rocks are the projects of partial to complete recrystallization (metamorphism) of sandstones, shales, cherts and volcanic rocks. They generally have significantly different physical properties than their unmetamorphosed equivalents, and yield different soils.

The most abundant of these rocks are the semi-schists, derived from massive to thin-bedded sandstones. Semi-schists are coarsely foliated rocks that tend to split along parallel planes defined by parallel orientation of abundant tiny flakes of micaceous minerals that are products of the metamorphism. Phyllite, derived by metamorphism of shale and mudstone, is associated with the semi-schists in places.

Soils developed by weathering of the semi-schists and phyllite typically have a high content of clay minerals which determines the important physical properties of these soils. When they are wet, they become quite plastic, have little strength, and thus are particularly susceptible to downslope creep and other modes of landsliding. Indeed, these soils are so weak when wet that accumulations more than two or 3 feet deep on moderate slopes tend to exhibit evidence of landsliding.

Metachert (metamorphosed chert) is associated with the semi-schist and phyllite in many places as relatively small, isolated masses up to about 100 feet long. In a few places like the southwestern slopes of Tiburon Peninsula, the metachert occurs in much larger masses. The metachert yields thin rock soils and colluvium that have relatively high slope stability, except where interbedded with abundant phyllite. In the latter case, clay derived from weathered phyllite can be sufficiently abundant to lower the wet strength of the material and lead to creep or landslides on slopes.

Metavolcanic rocks are also present in places with or near semi-schists. These are compact, hard, fine-grained rocks that are mostly similar in appearance to greenstones of the Marin Headlands, but different in their mineralogy and in many physical properties. These are strong rocks, with high slope stability characteristics. Their soils are reddish brown in most places, and tend to be thin and rocky. The largest outcrops of these metavolcanic rocks are on the ridge crest north of Terra Linda, on Belvedere Island, and on the southern slopes of Tiburon Peninsula.

Novato conglomerate is a thick accumulation of well-rounded pebbles and boulders in a well-cemented sandy matrix. It is a strong and stable rock, capable of standing firm in very steep cuts. Weathering of the rock yields a thin, gravelly, permeable soil that is quite stable. The soil supports a rather dense oak forest that effectively protects it from serious erosion. However, on the characteristically steep slopes underlain by the conglomerate, the soil is potentially subject to rapid erosion when stripped of vegetation.

3. Sandstone and Shale

Most of the hills and ridges of the southern Novato area are underlain either by thick-bedded, massive, coarse-grained sandstone or by a sequence of thin beds of shale alternating with thin beds of fine-grained sandstone. Similar sandstone and shale formations are the most abundant rock types in Central and parts of Southern Marin.

Bedding planes seldom are visible in the massive sandstone, except in deep cuts, and even there the widely spaced fracture planes of joints and minor faults are commonly more evident than bedding. The faults are ancient ones -- not potentially active -- but significant in that they are places of weakness that should be recognized in any deep excavation.

Both the thinly bedded unit and the massive sandstone yield sandy or silty soils that are well drained. But slopes are so steep in most areas underlain by these rocks that soils remain thin and are removed by erosion about as fast as they form. Thus thick masses of the soils are rare except in swales near and at the base of the slopes. Although they are relatively stable and not given to landsliding under natural conditions, these sandy

soils are susceptible to liquefaction in local zones where saturated, either by unusually heavy rain or more commonly by drainage from streets and roads. They are also highly susceptible to erosion when stripped of their vegetative cover.

4. Alluvium

Unconsolidated sedimentary deposits of clay, silt, sand, and gravel underlie the main stream and valley bottoms in eastern Marin and along the coast. These deposits are all of Quarternary age (less than 5 million years old). Upstream from the ancient sea level contour, these deposits contain abundant coarse detritus (sand and gravel) along with the finer-grained clay and silt. These soils were eroded from the steep local watershed slopes and transported by flooding streams to the gently sloping alluvial fans and floodplains of the valleys. In contrast, the bay plains, marshlands, and mudflats of the bay are below sea level, and are predominantly silt and clay transported from the east by the Sacramento River and deposited from bay tide waters. These latter deposits are called bay mud, and are described later in the text.

Alluvial deposits of the area are rarely well exposed, even in the banks of deeply incised streams. Although they are moderately well compacted, these deposits are unconsolidated and relatively weak, so they tend to slump when undercut by stream erosion. Where observed, they consist of interbedded layers of silty or sandy clay, clayey sand, and gravel. The deposits vary in composition and texture from valley to valley, depending on the nature of the different rock materials being eroded from the various local watersheds. Most of the alluvium in eastern Marin is rich in clay derived from the clay-rich soils that form on simi-schist and melange. In the southern part of the Novato area, however, the alluvial deposits consist of sandy layers interbedded with gravel, with a small percentage of clay, due to their derivation from the local sandy soils from slopes underlain mostly by coarse-grained arkosic sandstones.

5. Colluvium

Colluvium is a general term for deposits of unsorted and unconsolidated soil material and weathered rock fragments that accumulate on or at the base of slopes by gravitational or slope wash processes. Soil and rock debris in colluvial deposits were derived by weathering and decomposition of the bedrock materials underlying the slopes on which they lie, and are present on most slopes in the southeastern Marin area. Rapid erosion prevents colluvium from accumulating to depths of more than a few feet on the steepest slopes in the area. However, it accumulates in deposits to many tens of feet in some ravines, draws, and swales that separate the spurs of the ridges.

6. Bay Mud

The present and former marshlands and mudflats bordering the bay in eastern Marin County are underlain by various and uneven thicknesses of bay mud. Substantial portions of the former wetlands exist behind dikes which were created for agricultural and industrial purposes. This mud is a soft, unconsolidated, water-saturated silty clay, containing peaty plant remains and mollusk shells. Its general physical characteristics have been appropriately pictured as "...semi-viscous materials similar to jelly which can easily change its geometric configuration" (Lee and Praszker, 1969, p. 47).

The characteristics of the bay mud are the result of its origin and youthful age. It has been deposited over the last 10,000 years during the post "Ice Age" creation of San Francisco Bay. Lenses of peat and peaty clay within the resulting bay mud deposits indicate intermittent marshy growths that were successively buried by the floods of new silt that accompanied surges in the rise of sea level.

About 7,000 years ago the sea had reached its present level and the topography of the old valley system region had been partially buried by the soft, water saturated, organic silty clay - bay mud. It has not had time to have the water squeezed out of it by slow, natural compaction processes.

Not only is bay mud highly compressible, but, when saturated, it will flow laterally under the influence of localized pressure such as thick fills placed on it over too short a period of time. Similar soft mud underlies the mudflats and marshlands at the head of Tomales Bay and of Bolinas Lagoon.

## IV. NATURAL HAZARDS

### A. SEISMIC HAZARDS

1. Nature of Earthquakes

Earthquakes are sudden releases of strain energy stores in the earth's bedrock. The energy originates in the geologic forces which cause the continents to change their relative positions on the earth's surface. Earthquakes represent adjustments between tectonic plates as they slip past one another to establish a new equilibrium. In the process, the features of local landscapes are created as mountains and ridges rise up and as valleys are formed.

Energy can be stored in the earth's crust because its bedrock formations are more or less elastic. Under pressure they may be permanently distorted, or they may store the energy for later release. Like the hard steel of springs or the wood of bows, they can

bend under pressure and hold the strain energy. They can release the pressure slowly, or they can "break" and release it rapidly, and often destructively.

Earthquakes occur when either the resistance of friction between rock masses is overcome along an existing crack (fault) or when the shear strength of the hard rock material is exceeded, and it "breaks". The main break of an earthquake may be signaled by foreshocks and followed by aftershocks.

The energy being received in local rock formations may be released almost as soon as it is generated or it may be accumulated and stored for long periods of time. The individual releases may be so small and gentle that they are detected only by sensitive instruments or measured as tectonic "creep", or they may be massive and so violent that they cause destruction over vast areas.

During an earthquake, opposite sides of the crack (fault) move relative to one another. The displacement may originate at great depth in the earth and be absorbed within the earth or it may propagate to the surface. The relative movement between the rock formations on either side of the fault may be horizontal, vertical, or a combination of the two.

2. <u>Effects of Earthquakes</u>

The instant an earthquake is triggered, a series of events which can have serious consequences for property and people is set into motion. From the location along the earthquake fault where energy is released (the "focus"), force is radiated outward in the form of waves which dissipate gradually. Near the focus, the forces may be strong enough to physically stress landforms and buildings, while at greater distances the waves can be detected only with instruments.

The force which radiates outward from an earthquake is transmitted through the hard rock crust in short, rapid vibrations. These are transformed into long, high amplitude motions when the waves enter soft ground materials. Sometimes the undulations are long and deep enough to be visible as they move across the surface. Amplitude of seismic ground waves is shown in Figure 3.

As previously noted, the shear movement within the earth's crust that occurs during most California earthquakes may cause surface displacement along an existing fault or result in the creation of new fault breaks. However, earthquakes that originate at great depths within the earth and earthquakes of Richter magnitude less than approximately 6.0 are generally not accompanied by surface faulting.

Faults are seldom single cracks but typically are braids of breaks that comprise shatter zones. These link to form networks composed of major and minor faults. A fault having recorded movement, or one which shows evidence of geologically recent displacement (within the last 10,000 years) is regarded as "active" and is more likely to generate a future earthquake than a fault which shows no signs of recent movement.

Although rock or ground rupture along a fault is dramatic, the physical effects of faulting are highly localized. Not so are the effects of ground shaking which are widespread and cause most earthquake damage. In a great earthquake, major damage from ground shaking can occur over one hundred miles from the source of the earthquake.

3. Intensity and Magnitude

Intensity is a description of the physical effects of earthquakes. The lowest intensity ratings are based on human reactions, such as "felt indoors by few". The highest intensities are measured by geologic effects, such as "broad fissures in wet ground, numerous and extensive landslides, and major surface faulting". The middle intensity range is based largely on the degree of damage to buildings and other structures. Intensity ratings are based on visual observation and are not measured with instruments. The scale used to measure the intensity of a quake is the Modified Mercalli Scale with intensities ranging from I to XII, as shown in Table 2.

A single earthquake can have different intensity ratings based on geologic conditions, structural design, or distance from the earthquake's epicenter. Specific locations may have an intensity rating of VIII due to soil conditions and building type while other locations affected by the same earthquake may only have an intensity of IV.

In 1932, Charles Richter developed a system of tables and charts to deduce from seismological instruments a method of measuring the magnitude of an earthquake. The measurement of magnitude assigns a number to the calculated energy release of the earthquake, allowing comparison of seismic events. By this method, an earthquake is rated independently of the place of observation. Magnitude derived from seismograph records, as measured on the Richter scale, is a unique value for each earthquake. The scale is logarithmic, and each whole unit represents an increase of about thirty times in the energy released. A comparison of the two scales is shown in Table 3.

## Table 2. Modified Mercalli Scale of Earthquake Intensities

| Intensity | Observation |
|---|---|
| I. | Shaking not felt. |
| II. | Shaking felt by those at rest. |
| III. | Felt by most people indoors: Some can estimate duration of shaking. |
| IV. | Felt by most people indoors. Hanging objects swing, windows or doors rattle, wooden walls and frames creak. |
| V.. | Felt by everyone indoors, many estimate duration of shaking. Standing autos rock. Crockery clashes, dishes rattle or glasses clink. Doors close, open or swing. |
| VI. | Felt by everyone indoors and by most people outdoors. Many now estimate not only the duration of shaking but also its direction and have no doubt as to its cause. Sleepers awaken. Liquids disturbed, some spilled. Small unstable objects displaced. Weak plaster and weak materials crack. |
| VII. | Many are frightened and run outdoors. People walk unsteadily. Pictures thrown off walls, books off shelves. Dishes or glasses broken. Weak chimneys break off roof line. Plaster, loose bricks, and unbraced parapets fall. Concrete irrigation ditches damaged. |
| VIII. | Difficult to stand. Shaking noticed by auto drivers. Waves on ponds. Small slides and caving in along sand or gravel banks. Stucco and some masonry walls fail. Chimneys, factory stacks, towers, elevated tanks twist or fall. Frame houses move on foundations, loose panel walls thrown out. |
| IX. | General fright, people thrown to the ground. Steering of autos affected. Branches broken from trees. General damage to foundations and frame structures. Reservoirs seriously damaged. Underground pipes broken. |
| X. | General panic. Conspicuous cracks in ground. Most masonry and frame structures are destroyed. Serious damage to dams, railroads bent slightly. Some well-built wooden structures and bridges destroyed. |
| XI. | General panic. Large landslides, water thrown out of canals, rivers, lakes. Sand and mud shifted horizontally on beaches and flat land. General destruction of buildings. Underground pipelines completely out of service, railroads bent greatly. |
| XII. | General panic. Damage nearly total. Large rock masses displaced. Lines of sight and level disgorged. Objects thrown into air. The ultimate catastrophe. |

## Table 3. Intensity vs. Magnitude

Although no direct correlation can be made between intensity and magnitude, it certainly is true, at least for shallow-focus earthquakes (most California earthquakes), that the zone of destruction increases as the magnitude increases.

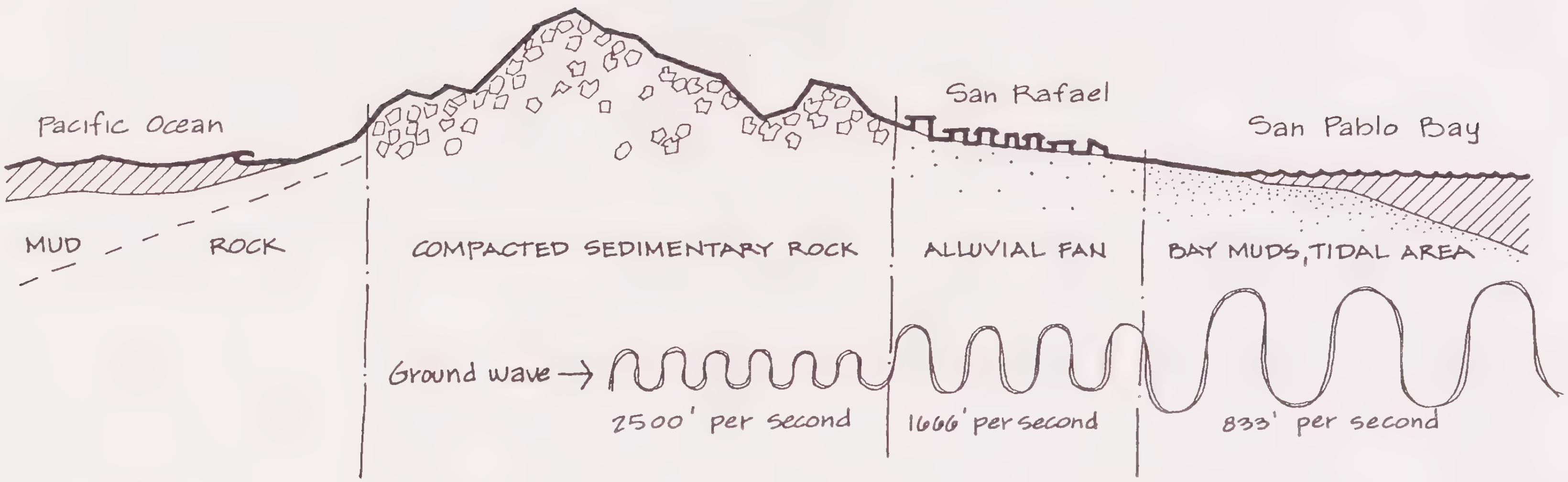
In 1958, Richter proposed the following comparisons for earthquakes occurring in Southern California:

| Magnitude: | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|
| Intensity: | I-II | III | V | VI-VII | VII-VIII | IX-X | X-XII |

The table below shows the relationship of earthquake magnitude and intensity:

| Area | Year | Magnitude | Intensity | Zone of Destruction |
|---|---|---|---|---|
| San Francisco | 1906 | 8.3 | VII | Extended out approximately 85 miles from the fault plane. |
| Kern County | 1952 | 7.7 | VII | Extended out approximately 50 miles from the fault plane. |
| Parkfield | 1966 | 5.5 | VII | Extended out about 5 miles from the fault plane. An earlier earthquake of Magnitude 5.1 caused only mild alarm and no apparent damage. |
| San Fernando | 1971 | 6.6 | VII | Extended out approximately 15 miles from the fault plane. |
| Loma Prieta | 1989 | 7.1 | VII-VIII | Extended 18 miles from fault plane. |

**Figure 3. Amplitude of Seismic Ground Waves**




The relative frequency, amplitude, and duration of ground waves increases as it passes from highly compacted material to less compacted material. Therefore, ground shaking will last longer and have a greater amplitude in the bay muds than in the hills underlying sedimentary rock.

## 4. Faults

California is located in one of the most seismically active areas of the earth, on the boundary between the plate underlying the Pacific Ocean and the one forming the American continent and the western North Atlantic Ocean floor. The Americas Plate, as the latter is called, is thought to be "drifting" southwesterly relative to the Pacific Plate and being forced to override the latter. The main line of contact between the two plates is the San Andreas Fault system. As these plates shove and grind against one another, movement occurs on the San Andreas Fault or a fault parallel to it and causes earthquakes.

The San Andreas Fault runs northwesterly through the Bay Area. It is paralleled by the Hayward, Calaveras and other major faults. These faults comprise a system which collectively has given rise to at least one documented "great" earthquake (1906) and from four to eight other major or great earthquakes since 1800, based on historical records of felt intensity. It must be remembered that until 1906 there were no instrumental measurements of earthquake magnitude. Bay Area fault traces are shown in Figure 4.

Other than the San Andreas Fault, no active faults are known within Marin County (see Figure 5). However, most of the County is sandwiched between two major active faults zones, the San Andreas and the Hayward, both of which have generated great earthquakes during the 200 years of our recorded history of the area.

The greatest Bay Area earthquake about which detailed quantitative information has been established is the April 18, 1906, shock on the San Andreas Fault, which has been rated at 8.25 magnitude on the Richter scale. San Francisco suffered well known spectacular property damage and some 450 direct or indirect deaths from that earthquake, while Santa Rosa and other less built-up urban areas also experienced substantial property losses to a lesser extent. Marin, was more sparsely inhabitated, particularly in the rural areas along the San Andreas Fault itself, and experienced relatively moderate property losses and 2 deaths.

The 1906 earthquake was the last significant seismic event with its epicenter located in Marin or which produced significant damage or ground movement phenomena in Marin, although minor effects of moderate Bay Area shocks with epicenters elsewhere were felt in parts of Marin. The Loma Prieta earthquake on October 17, 1989 registered 7.1 on the Richter Scale and is the most costly earthquake in San Francisco since 1906.

## Figure 4. Fault Traces in the San Francisco Bay Region

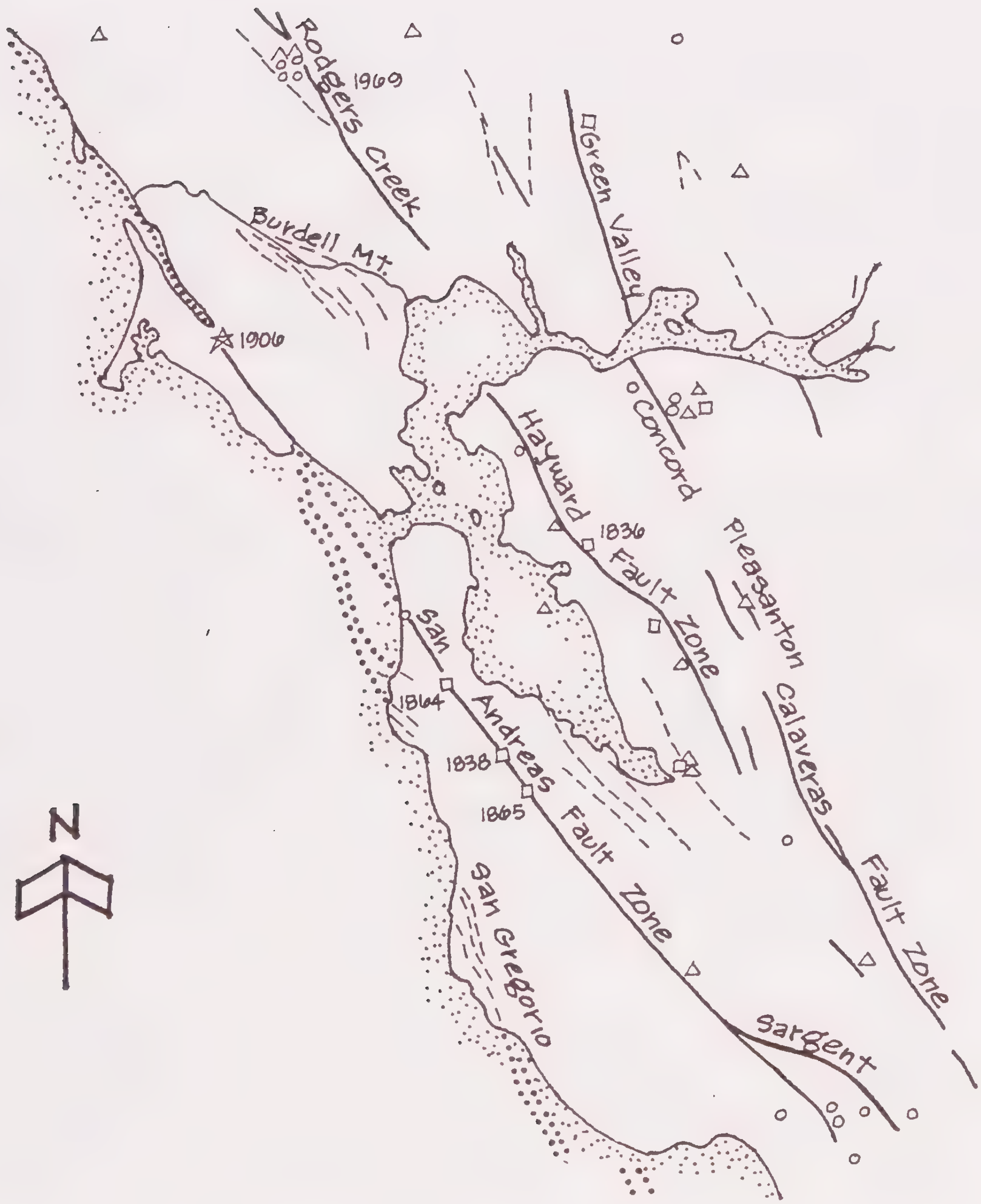
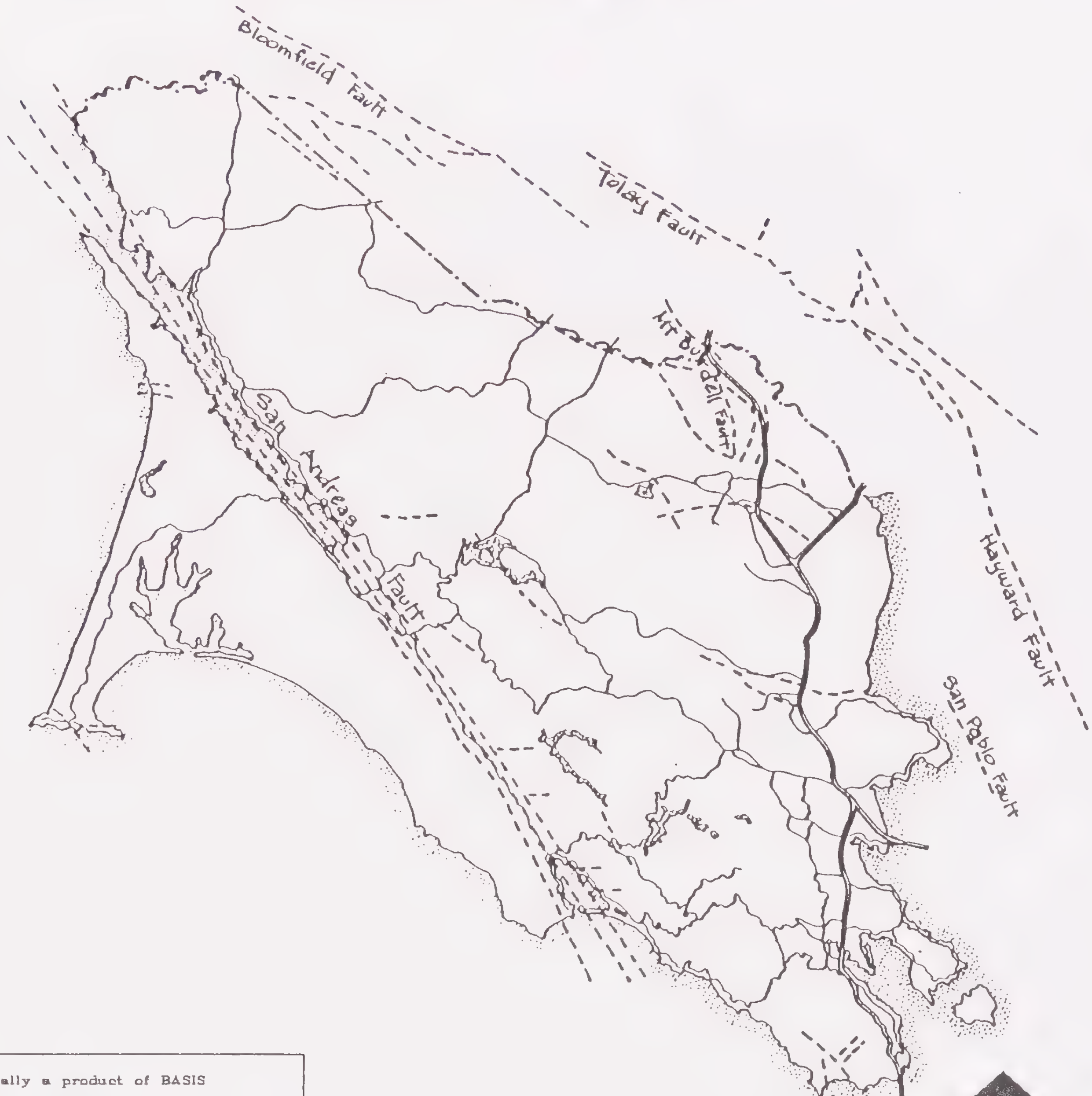


**Figure 5.** **Fault Traces in Marin County and Adjacent Areas**

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Marin County Planning Department

While the San Andreas Fault is the only proven active fault in Marin County, there is one other local fault zone - Burdell Mountain - for which some evidence exists of activity within the last 10,000 years. The activity is found primarily in the upland areas, and particularly in some youthful-appearing topographic features northwest of Rancho Olompali. Evidence is discussed in some detail in the 1975 report on geologic hazards in the Novato area prepared by the State for Marin County (see references). While there is as yet no definitive determination that this is an active fault, the evidence is suggestive enough to be kept in mind when developing land use polices in the vicinity of the zone.

5. Types of Seismic Hazard

In general, there four broad aspects of seismic risk to the human environment are present in Marin County: l) rupture of the ground surface by displacement along active faults; 2) shaking of the ground caused by passage of seismic waves through the earth; 3) ground failure induced by shaking, such as landslides, liquefaction and subsidence of unstable ground, with associated secondary destructive and disruptive effects, especially fire and disruption of utilities and transportation routes; and 4) tsunamis and seiches (see Environmental Hazards Technical Report # 1, Flood Hazards). These hazards are discussed below:

a. *Ground Rupture and Surface Displacement*. Although the danger to structures as a result of surface displacement along faults passing directly beneath them is a real one in California, ground rupture will always account for only a small percentage of earthquake damage, even in areas traversed by active faults. Ground rupture along fault traces usually occurs only during moderate to great (Richter 5.3-7.7) quakes, with the probability of rupture increasing with magnitude. The length of ground rupture and amount of displacement is generally related to both earthquake magnitude and the total length of the fault.

   Surface fault movement is not always rapid or a result of a major earthquake. Imperceptibly slow movement, called "fault creep" occurs along the Hayward and Calaveras Faults, and some other faults and may be accompanied by microearthquakes. Similarly, not all deformation of the earth's surface produces fault displacements. Strains in the earth deform the rocks until their strength is exceeded and they rupture, producing the earthquake. Accompanying this bending, however, is a certain amount of plastic deformation. Both rupture and plastic deformation commonly occur along active fault zones and may be sufficient to

damage or destroy structures over strongly deformed rocks. Earthquakes deep within the earth may result from rupture of deeply buried rocks but without fault displacement at the ground surface, although the surface rocks may be deformed.

There is little doubt that the San Andreas fault zone in Marin has seen repeated ground rupture and displacements in geologically "recent" time. The only such ground movements for which we have recorded observations, however, occurred in the great California earthquake of 1906. The displacements seen at that time were among the most striking ever documented, including the maximum reported horizontal displacement of 15-20 feet near the head of Tomales Bay. For most of its lineal traverse across West Marin, the 1906 earthquake produced a visible rupture trace consisting primarily of a ridge 3 to 10 feet wide within a few inches to 1.5 feet high, or by a trench averaging less than a foot deep and systems of branching and simple straight surface cracks.

Some of the cracks showed vertical throws up to 6 feet high and openings up to 6 inches remaining months after the event. No observation of ground rupture or displacement was reported in East Marin, although ground shaking caused moderate but widespread damage.

While it is true that earthquake damage resulting directly from ground displacement accounts for only a small percentage of all damage, the destructiveness of surface rupture is significant where it does occur. The classic definitive account of the 1906 earthquake, the Report of the State Earthquake Investigation Commission by Lawson, Gilbert, et al. (Carnegie Institute Report) documents the impressive destructive effects of 8 to 15 feet horizontal displacements on barns, rural houses, roads and fences. This destruction was most evident in Bolinas, Tomales, and the ranch structures of the Olema Valley and to a lesser extent in Inverness and Point Reyes Station.

With this experience in mind, the California State Legislature included the San Andreas fault zone in the area governed by the provisions of the Alquist-Priolo Geologic Hazard Zones Act of 1972. The Act prohibits any new construction for human occupancy across known traces of specified active faults or within a minimum 50 foot distance of such traces. The 50-foot building

setback is determined by geologic investigation of individual sites when development or construction of four or more single-family houses is proposed. Figure 6 illustrates the Alquist-Priolo maps and Figure 7 is a key map of areas covered by these requirements.

b. *Ground Shaking*. It has long been recognized that the intensity of ground shaking during earthquakes and the associated damage to buildings is profoundly influenced by local geologic and soil conditions. Data from past earthquakes has shown that the intensity of ground shaking can be several times larger on sites underlain by thick deposits of saturated sediments than on bedrock. Consequently, the greatest losses resulting solely from shaking may occur where tall structures are built on thick and relatively soft, saturated sediments. Losses are least where they are built on firm bedrock. In addition to the amplification effects of local geologic deposits, the amount of ground shaking at a particular site depends both on characteristics of the earthquake source (for example, magnitude, location, and area of causative fault surface) and distance from the fault. To anticipate the severity of ground shaking likely to occur at a site, each of these factors must be taken into account. Damage which results from shaking is also a function of the structural integrity of buildings before the earthquake, (discussed in Section IV.C. of this report). Figures 8 and 9 show areas subject to ground shaking.

c. *Ground Failure and Related Secondary Effects.* Liquefaction, lateral spreading, landsliding, lurching, differential settlement, and bedrock shattering are grouped within the general phenomenon called ground failure. All of these involve a displacement of the ground surface due to loss of strength or failure of the underlying materials during earthquake shaking.

Some of these phenomena, particularly landslides and differential settlement, commonly occur in Marin without a triggering seismic event. These occurrences are discussed later in this section.

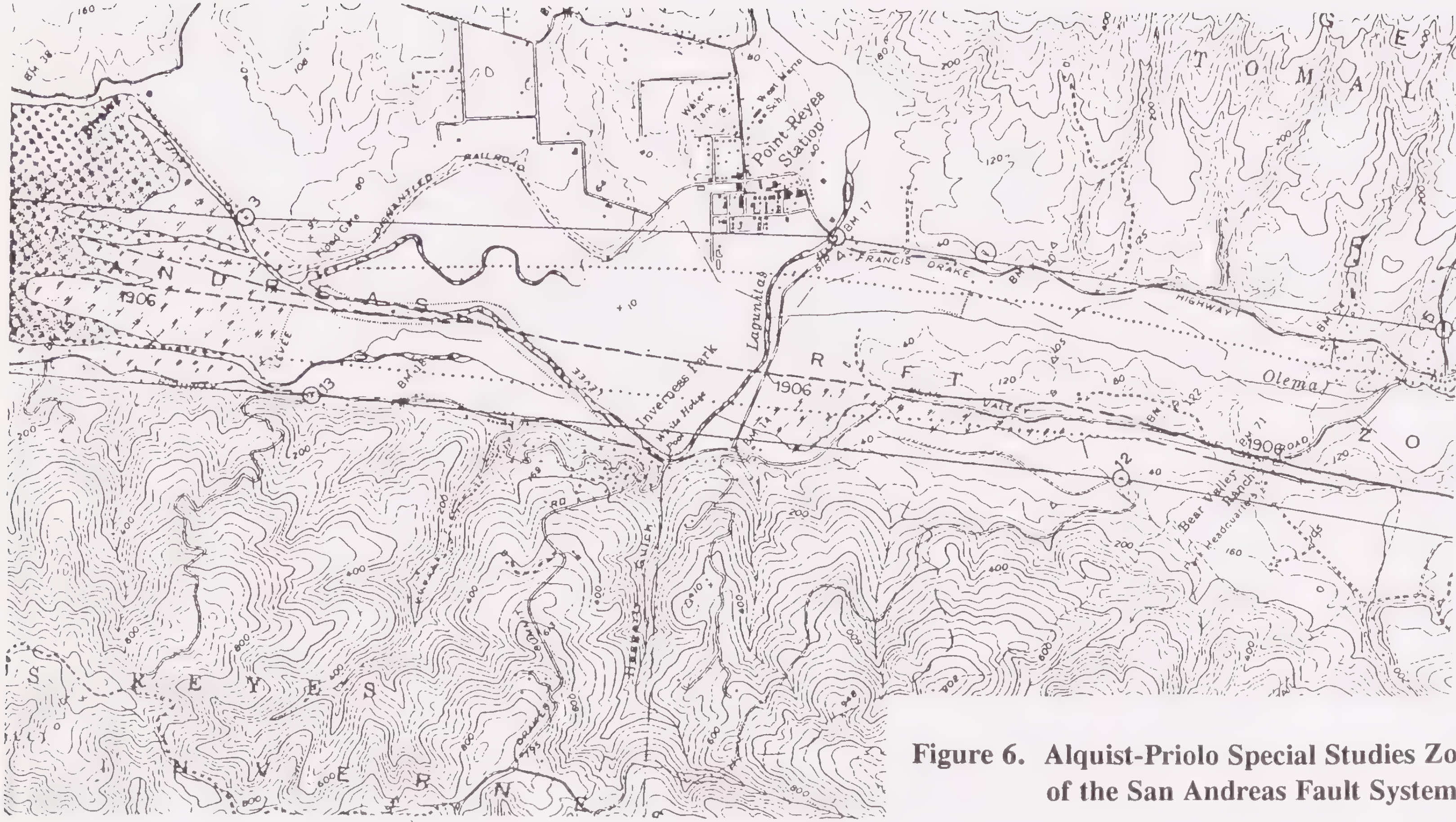


Figure 6. Alquist-Priolo Special Studies Zone of the San Andreas Fault System

**Figure 7. Key Map of Areas Covered by Alquist-Priolo Special Studies Zones Requirements**

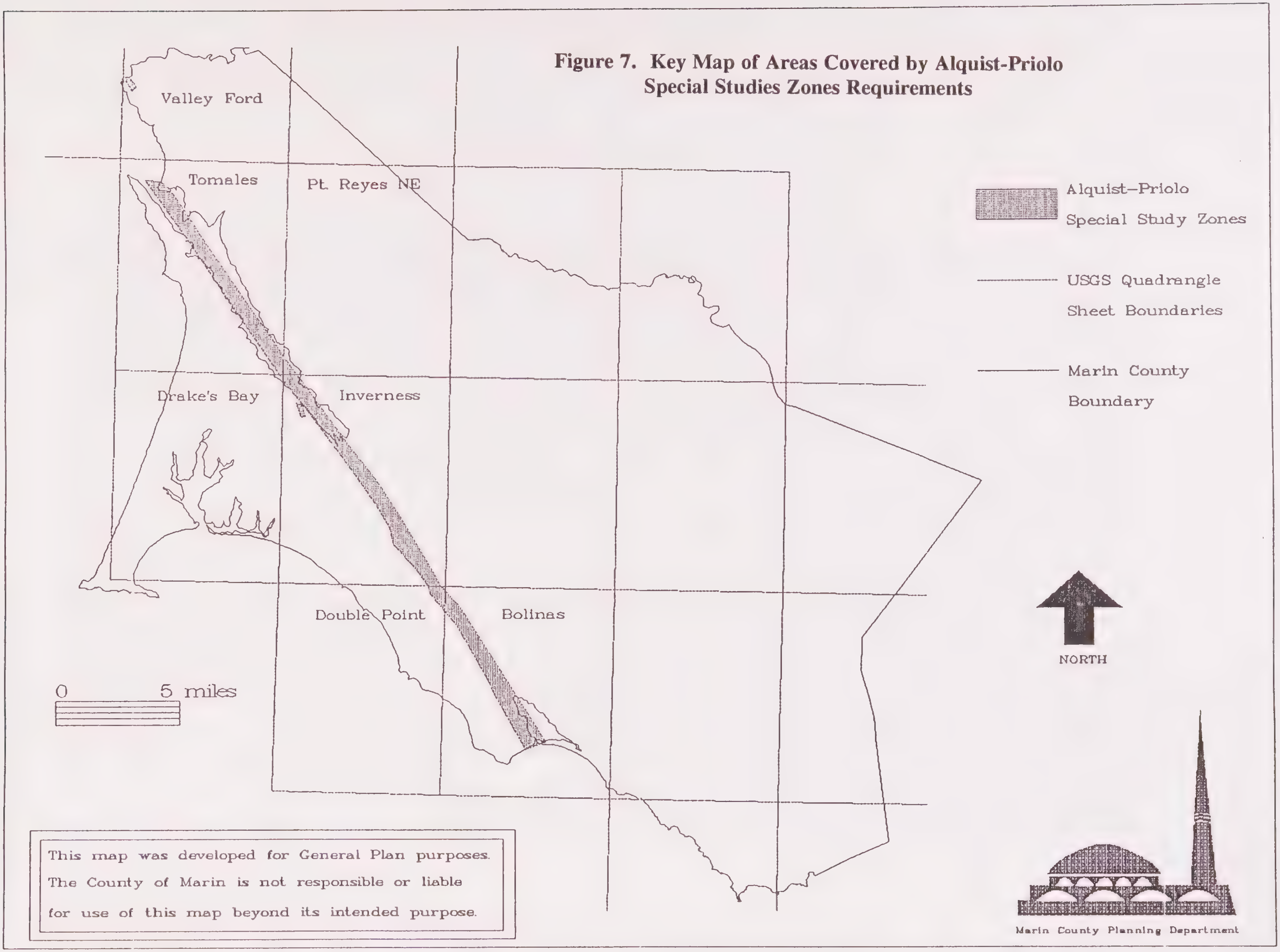

**Figure 8. Geologic Units Susceptible to Ground Shaking**

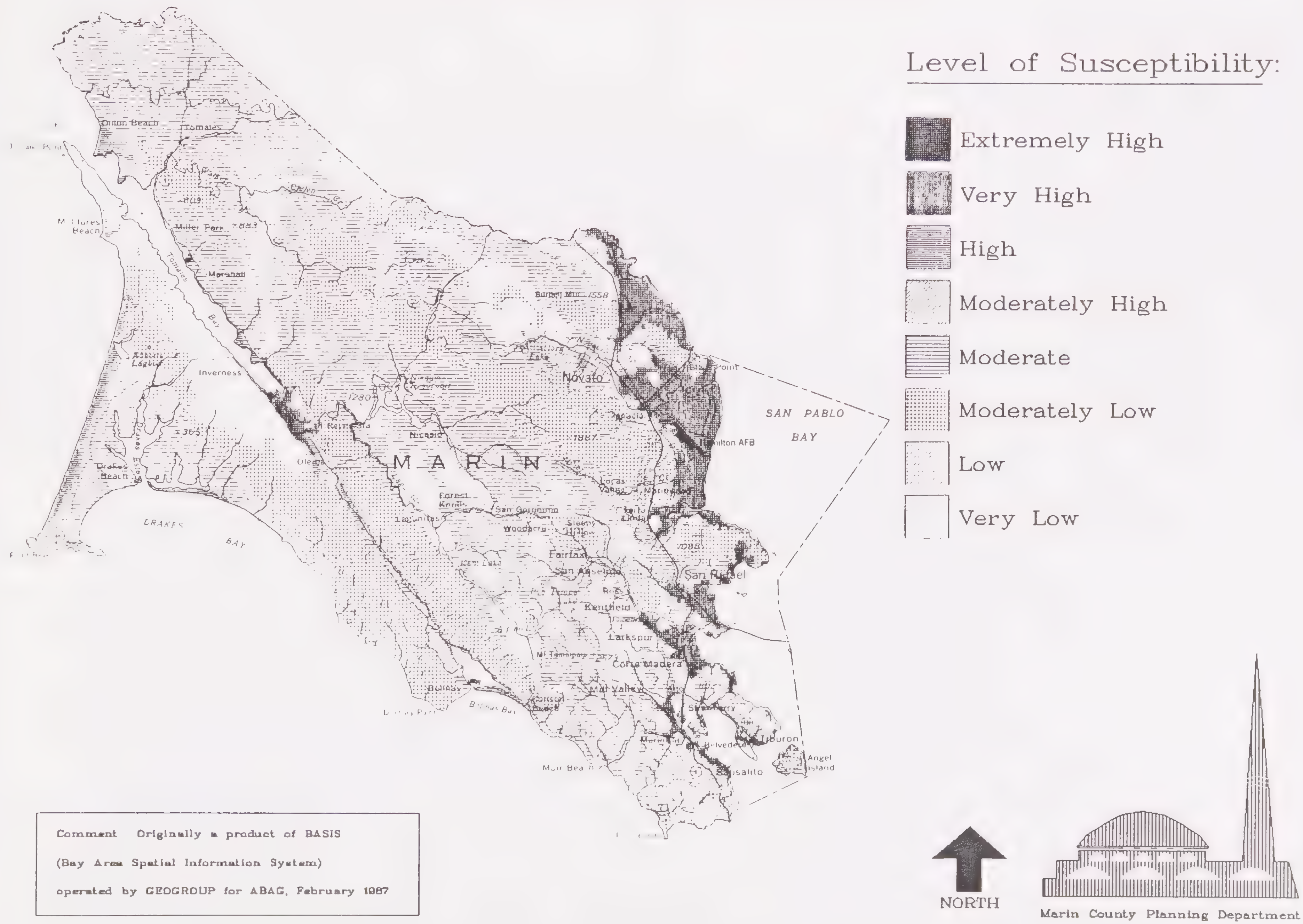


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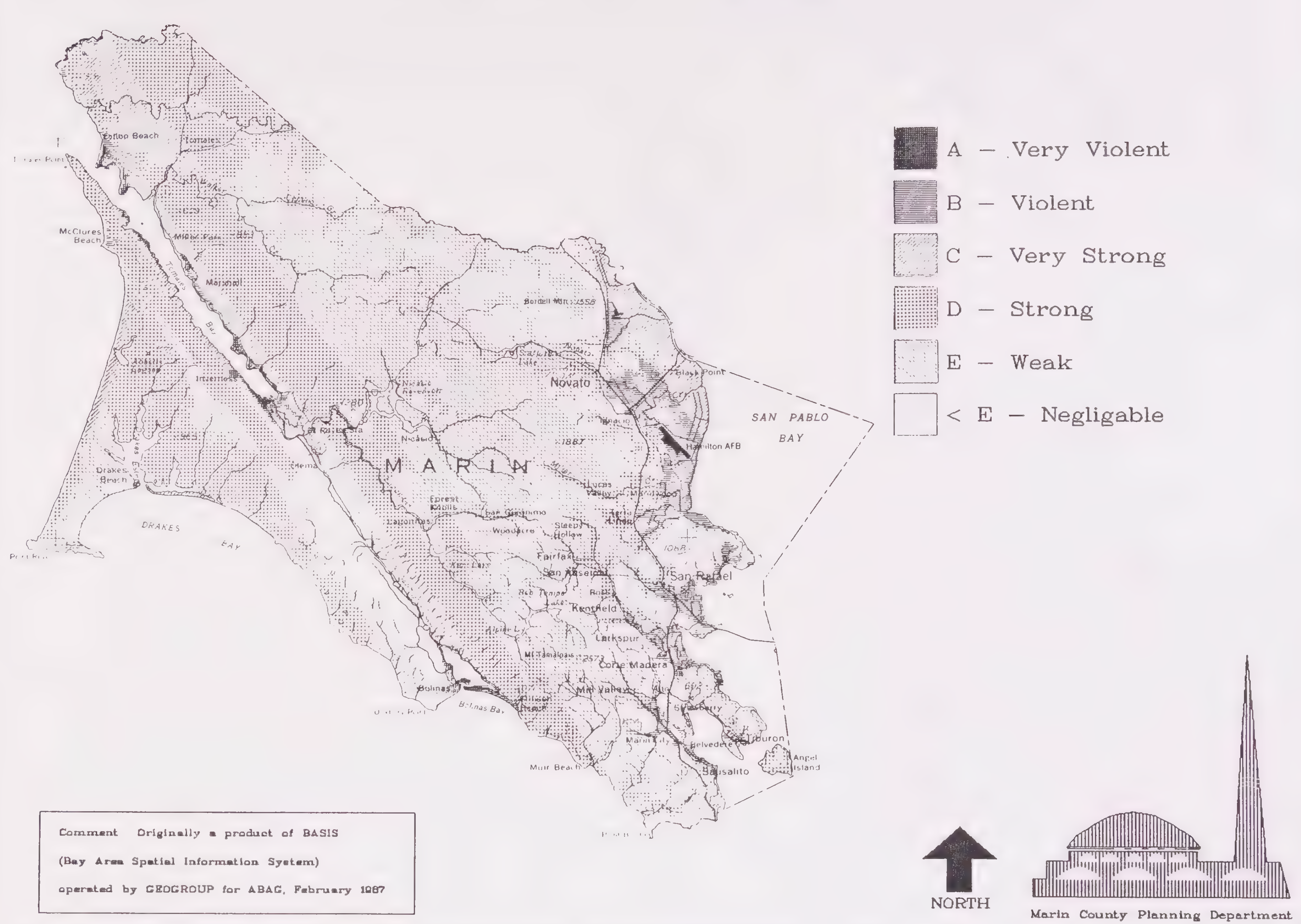
**Figure 9. Maximum Ground Shaking Intensity**

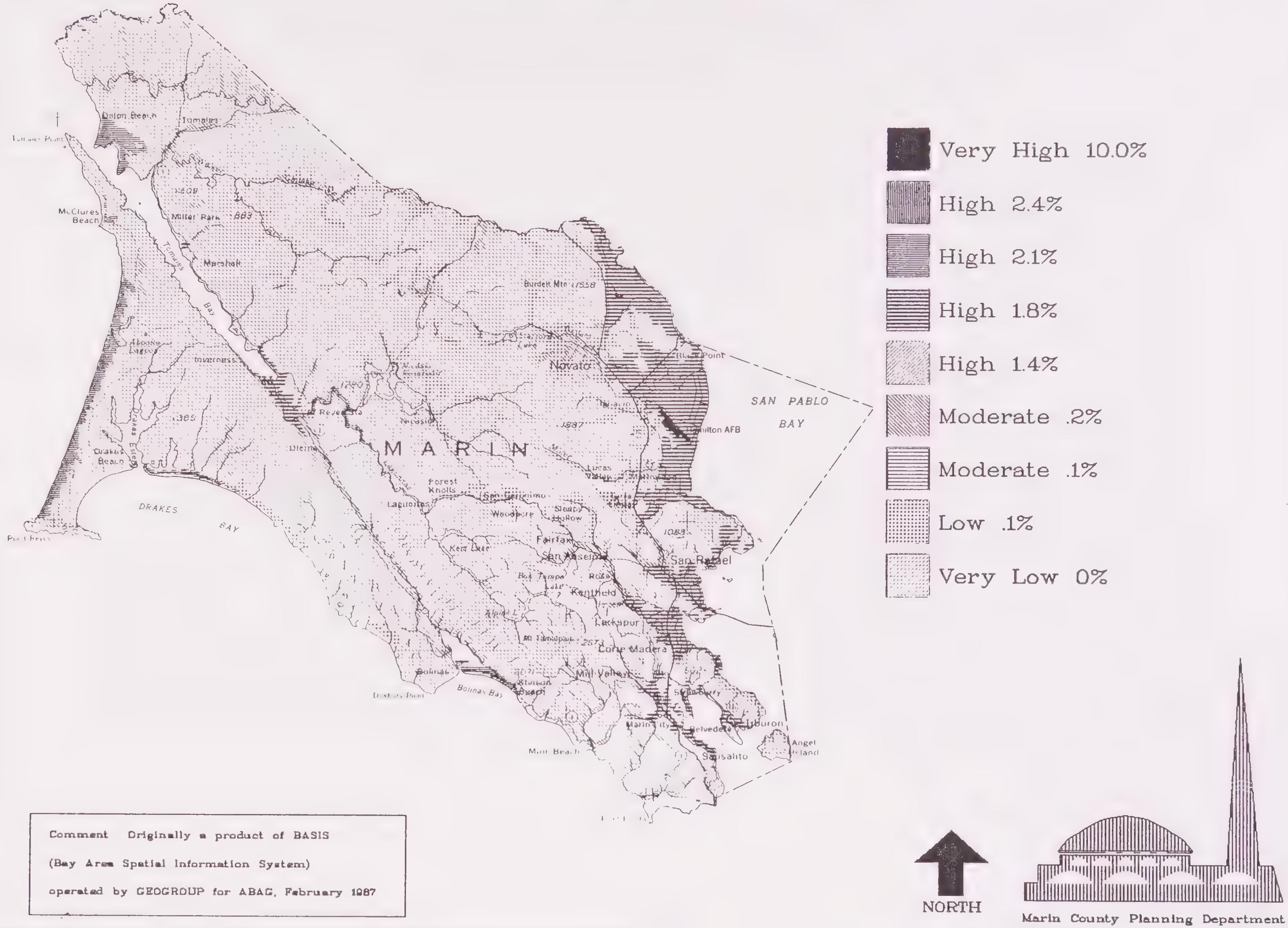


Liquefaction is a common mechanism causing many types of ground failure and it occurs when the strength of saturated, loose granular materials (silt, sand, or gravel) is dramatically reduced, as may occur during an earthquake. The earthquake-induced deformation transforms a stable granular material into a fluid-like state in which the solid particles are virtually in suspension, similar to quicksand. Figure 10 shows liquefaction susceptibility. In Marin, the liquefaction-prone geological materials, in order of decreasing susceptibility, are artificial fill, sand, and alluvium. The bay mud is least stable where lenses of sand are present, although the extent to which clay is present is considered to be an important deterrent to liquefaction since the clay tends to bind the sand together. Alluvium is least stable in deep water-saturated deposits. Areas underlain by hard bedrock at shallow depth are seldom subject to liquefaction.

Loss of strength in fine-grained cohesive materials is another mechanism of ground or foundation failure and manifests itself in squeezing or "lateral spreading" of soft, saturated clays, such as San Francisco Bay mud. It can result in rapid or gradual loss of strength in the foundation materials. Structures can either gradually settle or break up as foundation soils flow laterally.

Landslides involve downslope movement of soil and rock material and include a wide variety of materials and mechanisms ranging from rockfalls to earthflows. Earthquake-induced landslides will occur generally in the same marginally stable areas as landslides induced by other natural energy sources, such as intense rainfall, and may be indistinguishable from them in appearance. The addition of earthquake energy may induce landslides that otherwise might not have occurred until a future rainy season. Landslides on hillsides are due to failure of either surface material (soil, colluvium) or bedrock, or both. Landslides in areas of low slope angles can result from liquefaction of subsurface sand layers during earthquakes. Natural slopes, even very steep ones, that are underlain by bedrock and do not have existing significant landslides, can be expected to exhibit a high degree of stability during earthquakes. In places, however, such slopes have been undermined by deep, sometimes vertical cuts for highway, streets, and quarries and some of these will be the scenes of rock falls or other forms of slope failure under the influence of strong earthquake vibrations.

# Figure 10. Liquefaction Susceptibility



Other forms of ground failure that may be caused by earthquake shaking include lurching and differential settlement. Differential settlement is uneven settlement that can occur with time or during earthquake shaking in poorly consolidated granular soils adjacent to bedrock. Lurching involves the cracking and lateral movement of unstable slopes toward an unsupported free face during earthquake shaking.

d. *Tsunami and Seiche Effects.* Tsunamis and seiche are discussed in more detail in the Environmental Hazards Element Technical Report # 1, Flood Hazards. Tsunamis are large ocean waves generated by rapid changes in elevation of large masses of earth and ocean, such as occurs with vertical faulting beneath the ocean. Seismic seiches, or earthquake-generated standing waves, occur within enclosed or restricted bodies of water (lakes, reservoirs, bays and rivers). They can be likened to the oscillations produced by the sloshing of water in a bowl or a bucket when it is shaken or jarred. Seiche waves generally have a low amplitude (less than a foot), but in shallow areas or where the water is constricted, wave runup can be as great as 20 or 30 feet (McCulloch, 1966).

## B. NON-SEISMIC GEOLOGIC HAZARDS

Marin County, particularly its eastern, suburbanized corridor, has two contrasting topographic settings that define sharply contrasting geologic conditions and stability problems which exist independent of any triggering seismic event. These are:

Other steep hills and ridges which are subject to landslides and downhill creep;

The bay plains, marshlands, and mud flats subject to subsidence and differential settlement.

### 1. Landslides

Landslides are not random. They occur in certain areas for specific and relatively predictable reasons. Likelihood of this hazard should be accounted for in land use planning and site development. Landslides and swelling soils constitute the principal geologic hazards to structure, roads and utilities in the uplands of Marin County. Both are widely but unevenly distributed in the area and both are related to the bedrock geology and the surface soils and colluvium derived by weathering of the bedrock.

A landslide is defined here as the downslope movement of soil and rock material en masse under the influence of gravity. Several varieties of landslides are a major geologic hazard to any works of man constructed on, adjacent to, upslope of, or in the downslope path of landslides. The principal conditions that affect slope stability and the formation of landslides are decomposition of the earth materials underlying the slope, slope steepness, the concentration of surface and ground water, earthquakes, and activities of man. Human activities that may cause landslides include slopes cut too steep, improper placement of fill on slopes, concentrating surface runoff or injecting water into the ground. The most common landslides affecting Marin County include earthflows, debris flows, and debris avalanches, all of which are restricted to soil and loose rock over bedrock. Some bedrock blocks landslides, which are masses of bedrock that have moved downslope are also located in Marin County.

Earthflows are landslides that occur in clayey soils and move slowly downslope at velocities of a few meters or less per day. Earthflows are often associated with soils derived from Franciscan melange. Debris flows are associated with sandy soils and move more rapidly downslope than earthflows, usually during a single episode lasting a few minutes or hours. Debris flows usually occur in soils derived from the sandstone and shale bedrock unit.

The hills and ridges of eastern Marin sharply differ from place to place in the strength and relative stability of the rock formations and other geologic materials that underlie the surface. Even when the identity of the underlying materials is not known, these differences in strength and stability can generally be inferred by the presence, absence, or relative abundance of landslides on the various slopes. Where landslides are abundant, the slopes are likely to be inherently unstable; where landslides are few or lacking on the steep slopes characteristic of eastern Marin, the slopes are relatively stable. Even in those areas where very steep natural slopes have relatively few landslides, indiscriminate deep cuts, both for streets and house sites, can be expected to cause some serious and longterm problems. Adversely dipping fractures and bedding planes that are a part of the structure of the underlying rock may become planes of movement when undercut.

Landslide deposits are widely but unequally distributed in eastern Marin County. These surficial deposits of rock or soil materials have separated from their original position on slopes and have moved downslope under the influence of gravity. They exhibit characteristic topographic expressions that result from the downward and outward displacements of the landslide masses. Prominent topographic features that commonly develop in landsliding include scarps, terrace-like benches that commonly have topographic sags or depressions on them, hummocky or disrupted ground surfaces, and anomalous drainage patterns.

Most landslide deposits in Marin County are debris flows but many or most of these are composite in their development. Typically such landslides originate as rotational slumps, but disintegrate with further movement into debris flows. On unstable slopes, many such landslides commonly merge to form aprons of these deposits in which individual landslides are difficult or impossible to distinguish.

Where their topographic expressions have been modified or masked by erosion, forest cover, or grading operations, most landslide deposits can be identified from exposures in gullys, road cuts, or other excavations. This is because they are typically composed of chaotic mixtures of angular rock fragments of various sizes and orientations that are embedded in an unconsolidated, fine-grained, and clay-rich matrix. One type of landslide, the debris avalanche, leaves behind as the only evidence of its occurrence a scar that can be recognized a year or more after the event.

A typical soil debris avalanche in Marin County involves a few hundred cubic yards of soil and colluvium and is the result of total saturation of a part of the hillside. Debris avalanche landslides are probably the most hazardous type of landslide effecting Marin County. Although similar to debris flows, debris avalanches move more rapidly, with single episodes that last only seconds. They occur suddenly in over-saturated sandy or silty soils, such as those derived from the sandstone and shale unit.

The soils tend to liquefy and flow rapidly downslope at speeds of up to 20 miles per hour. Because of their highly fluid nature, debris avalanches travel long distances and are controlled by drainage channels and canyons. The avalanche mass is so fluid that it flows to the base of the slope, or beyond, and spreads out as a thin coating of mud over the surface. In general, it occurs only in sandy and silty soil that has little clay content. The highly fluid nature of these flows leads them to follow gulches and creek canyons to the base of the slope; so that the mouths of such gulches and canyons at the base of sandstone ridges, such as Big Rock Ridge and San Pedro Ridge, are highly vulnerable to such avalanches.

During the last 20 years, debris flows have occurred abundantly in Marin County when about 4 inches or more of rain have fallen in 10 hours or less. In some areas, however, they have occurred during normal rainfall as a result of excessive water introduced into the susceptible hillsides by domestic water use. Houses in the County have suffered damage or destruction from these avalanches both by being struck by the fast moving flows and by being undermined because foundations were embedded in the soil that liquefied, rather than in the bedrock beneath the soil.

Most landslide damage in Marin County has taken place within pre-existing landslide deposits as a result of continuing or renewed movement within them. The great majority of these damaging landslides are soil and rock debris flows developed on slopes underlain by Franciscan melange. Their heaving soils and slow downslope movements strain houses by cracking foundations, and crack and disrupt streets and utilities. Most of the landslide deposits that show on Marin County maps are of this type. Types of landslides and the estimated relative abundance of landslides are shown in Figures 11 and 12.

### 2. Expansive and Creeping Soils

Soils that have a high clay content tend to be expansive. In other words, the clay tends to swell with increased moisture content and contract during dry spells. These volumetric changes with seasonal variations in moisture content can disrupt shallow foundations and pavements. On slopes, the annual swelling and shrinking of expansive soils causes the soil to migrate downslope at rates of a fraction of an inch per year. This downslope movement, known as soil creep, can disrupt foundations and utilities. Expansive and creeping soils should be identified prior to construction so that engineering measures can be implemented to minimize potential damage to structures. Soils that swell when wet and shrink when dry also cause considerable damage to structures and streets in some areas of Marin County.

In southeastern Marin County, these soils form in areas underlain by Franciscan melange where the fine-grained matrix of that unit is abundant. Such soils are dark gray in most places. In late summer they exhibit wide cracks one to three inches wide in many places, and at this time the soil is literally rock hard. Swelling of the clay minerals closes the cracks in the wet season, and the soil then is plastic and very weak. The forces exerted during expansion and contraction are sufficient to heave and distort buildings and to crack shallow foundations and pavements. Such soils should be recognized prior to construction, and special engineering methods used to help reduce the stresses on buildings. The expansion-contraction characteristic of these soils causes slow downslope creep of the surface where they lie on a slope, thus adding to their potential for disruption of structures and facilities. These soils are abundant in most landslide deposits that lie on melange slopes and are the principal reason for the inherent instability of such slope deposits.

### 3. Subsidence and Differential Settlement

The bay mud that underlies marshlands and mud flats (and many existing developments on fills placed upon such lands) is an unconsolidated, jelly-like material that is both highly compressible and subject to lateral flow when loads are placed on it.

**Figure 11. Types of Landslides Common to Marin County**

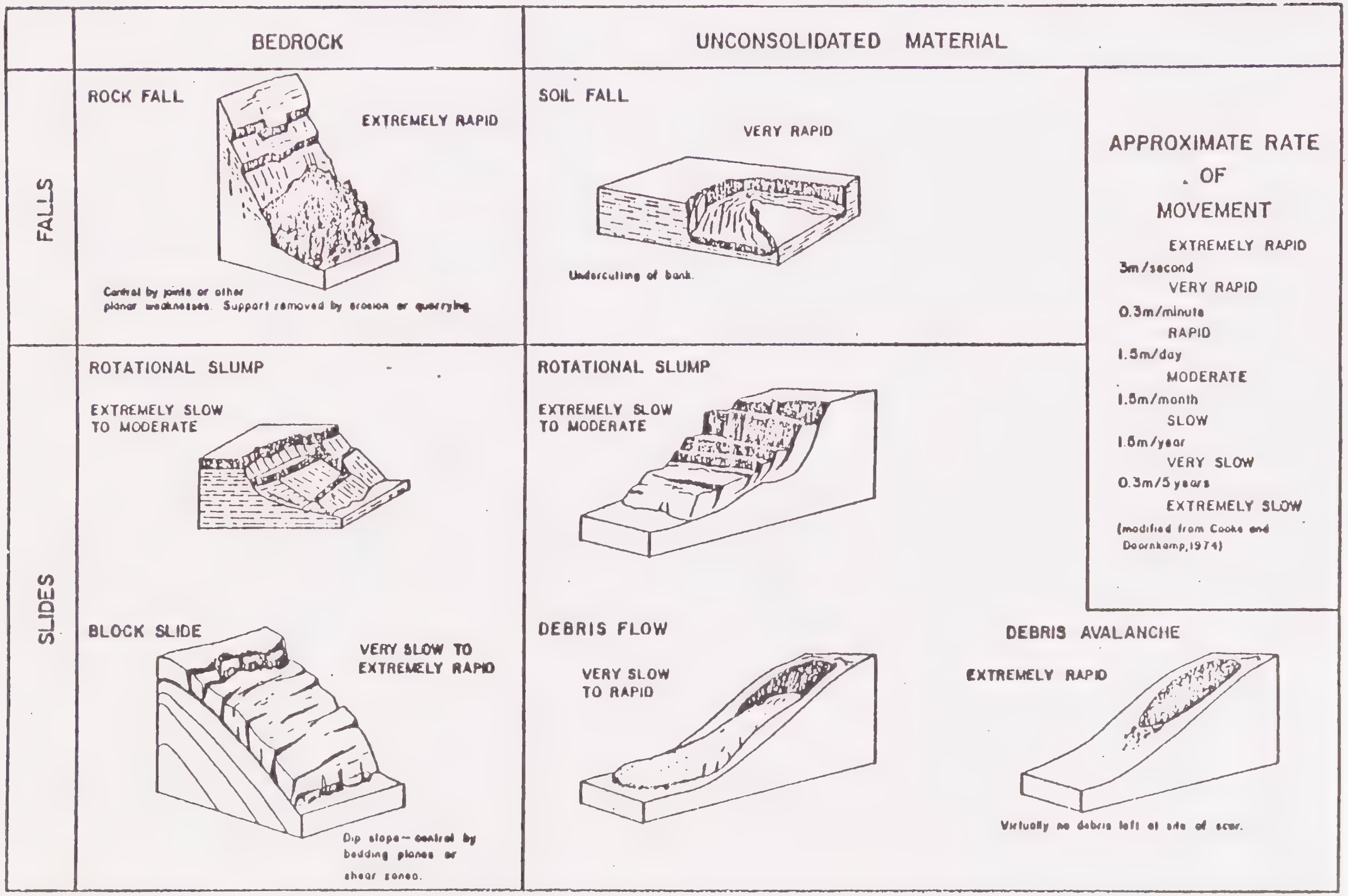
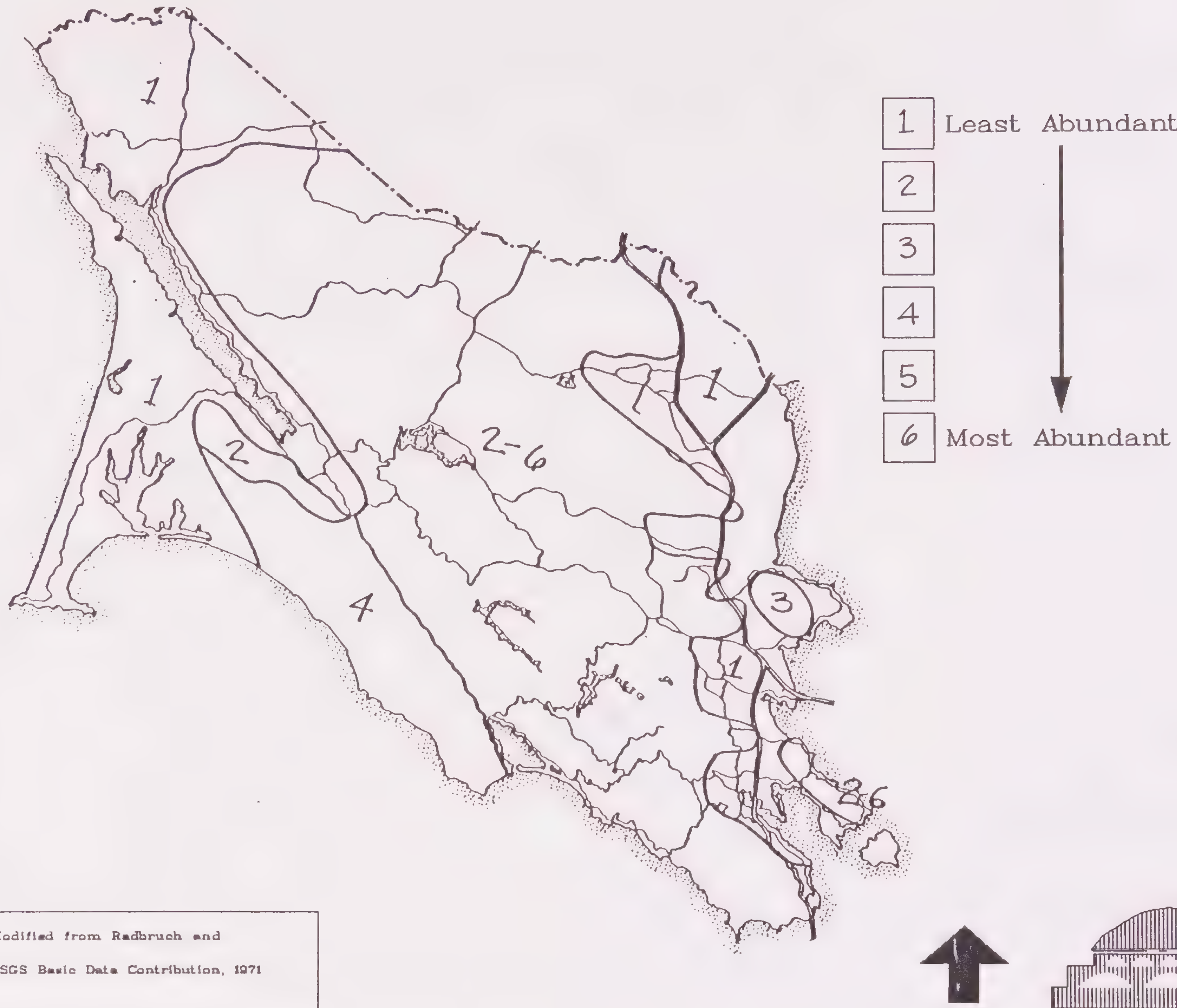


**Figure 12. Estimated Relative Abundance of Landslides In Marin County**




Comment Modified from Radbruch and Wentworth, USGS Basic Data Contribution, 1971

Marin County Planning Department

Developments on fill placed upon the marshlands and mud flats of San Francisco Bay are susceptible to several severe types of stability problems.

Differential (uneven) settlement may occur in poorly consolidated soils during earthquake shaking or over time. When settlement occurs over a large area, it is termed subsidence. Poorly compacted fills are quite susceptible to settlement. Developments on fill placed upon the marshlands and mud flats of San Francisco Bay are also susceptible to long term settlement or subsidence, as the underlying bay mud settles over time under the weight of the fill. Thick fills may settle a great degree within a short time, but require two centuries to achieve total compaction, while more shallow fills may settle in a shorter period. Such settlement may result in flooding as ground levels are lowered, or in damage to structures, utilities, and roadways. This is particularly significant given indications of rising sea levels (see Technical Report #1, Flood Hazards).

In most of the Bay Area, very early bay fills were placed haphazardly. Although recent fills have been placed with the aid of available technological skill, there still exist some uncertainties with regard to their ultimate behavior. Problems encountered range from tilted buildings, walls cracking, and vertical separation of buildings, to sinking of surrounding ground in the case of piled foundations.

4. Slope Stability

This section focuses on the mechanics of non-seismic slope instability as it is expressed in Marin's upland geologic setting. The description of the extent of hazard from unstable slopes is adapted from the extensive four-year geologic hazard investigation and mapping project covering eastern Marin undertaken for the County and cities by geologists of the California Division of Mines and Geology.

The principal factors considered in making the slope stability interpretive maps prepared by the State geologists for the County studies are:

- The broad stability characteristics of geological materials underlying the slopes;

- Steepness of slopes; and,

- The presence of active or intermittent natural forces that tend to cause slope failure.

The maps provide broad evaluations of land stability patterns which have been prepared to aid in general land use planning. Discussion of the uses and limitations of these maps will be found in the detailed explanatory legends on the map sheets (available at the Marin County Planning Department). Appendix 1 illustrates and lists areas covered by State and Federal geologic studies.

These judgments are interpretive, and apply generally to large areas. Within each area conditions may range locally in detail through all stability categories. Hence, an area designated zone 1 may contain unmapped local landslides, and an area designated zone 4 may contain relatively stable local sites. For example, some debris avalanche landslides that occurred in Marin County during the winters of 1982 and 1983 travelled thousands of feet crossing over all four zone areas, indicating that the effects of debris avalanche landslides are not reflected on the slope stability maps. Table 4 describes these zones.

## C. STRUCTURAL HAZARDS DUE TO EARTHQUAKES

### 1. Overview

California is in an era of increasing seismic activity, with damaging earthquakes occurring, on the average, every two years. Scientists say that after Los Angeles, the next most probable metropolitan region that may be struck by a major damaging earthquake is the San Francisco Bay Area. Here a disruptive earthquake can occur along any one of ten active faults with the Hayward and San Andreas Faults the most likely. The chance of a major damaging earthquake occurring in the next 25 years is about 50%.

The Bay Area Earthquake Preparedness Project of the California Division of Mines and Geology prepared documents analyzing fictional scenarios of the effects of an 8.3 earthquake on either the San Andreas or Hayward Faults. These reports estimate that 3,000 to 11,000 people might die and another 12,000 to 44,000 might require hospitalization if a major quake occurred along the northern section of the San Andreas Fault in the Bay Area. The earthquake could also cause approximately $38 billion in structural and property damage and indirect loss to business of nearly $100 billion.

In this earthquake scenario, Marin County is essentially cut in two. The quake topples freeway overpasses and buckles pavement on Highway 101 south of San Rafael. In addition, Highway 1 and the two main cross-county roads, Sir Francis Drake Boulevard and Lucas Valley Road, are blocked by landslides, trapping the people of West Marin. Although casualties in Marin are not as great as in more urbanized parts of the Bay Area, rescue work is anticipated to be difficult because of the geographically separated nature of the county's communities.

To reach pockets of stranded people, rescuers could be forced to push emergency roads through areas where none now exist. In this scenario, specific structures would be affected as follows:

- Petaluma River Bridge unsafe;
- Many overpasses on Highway 101 from San Rafael to Cotati closed or limited to light vehicles for 12 to 72 hours;
- Highway 37 closed for more than 72 hours at Sears Point and Novato Creek due to soil liquefaction;
- Hamilton Air Force Base closed between 72 hours and one week;
- Highway 101 between Richmond Bridge and San Rafael closed for 72 hours due to soil liquefaction;
- Shoreline Highway closed for 72 hours due to slides;
- Richardson Bay Bridge possibly closed for 12 hours due to sinking at both ends; and
- Slide at Waldo Grade and slumping at toll plaza close Golden Gate Bridge for 72 hours.

2. <u>Structural Hazards and Building Types</u>

Ground shaking can result in structural failure and collapse of structures or cause non-structural building elements, such as light fixtures, shelves, cornices, etc., to fall and present a hazard to building occupants and contents. The first building code regulations relating to earthquake resistance appeared in 1933. As knowledge has increased, codes have been updated; however the field of earthquake resistant structural engineering is very complex and relatively new. Compliance with provisions of the Uniform Building Code (UBC) should result in structures that do not collapse in an earthquake, although many structures in Marin County were built before the UBC contained provisions for seismic safety. Hazards associated with falling objects or non-structural building elements will remain.

## Table 4. Relative Slope Stability

| | |
|---|---|
| **Zone 1** *Most Stable* | Includes resistant rock that is exposed or is covered only by shallow colluvium or soil. Also in this zone are broad, relatively level areas along the tops of ridges or in valley bottoms. These areas may be underlain by material that is weak (such as Franciscan melange matrix and alluvium), but occupies a relatively stable position. Some landslide deposits that have moved to relatively stable positions at or beyond the base of the slopes from which they were derived are in zone 1. |
| **Zone 2** | Narrow ridge and spur crests underlain by relatively competent bedrock, but are flanked by steep, potentially unstable slopes. |
| **Zone 3** | Areas where the steepness of the slopes approaches the stability limits of the underlying geological materials. Some landslide deposits that appear to have relatively more stable positions than those classified within zone 4 are also shown here. |
| **Zone 4** *Least Stable* | Includes most landslide deposits in upslope areas, whether presently active or not, and slopes on which there is substantial evidence of downslope creep of the surface materials. These areas should be considered naturally unstable and subject to potential failure even in the absence of human activities and influences. Banks along deeply incised streams are also included in zone 4. |

Generally, older wood frame structures may perform relatively well, while unreinforced brick buildings probably do not meet current seismic safety standards, and may not withstand a major earthquake. These structures are primarily located in older developed areas of the County. The cost of reinforcing an existing unreinforced brick building can equal 50% of the cost of a new structure. The County currently reviews applications for changes of use and may require structural improvements to reduce the hazard of seismic failure. In 1986, the State passed legislation requiring local agencies to inventory unreinforced masonry buildings by January 1, 1990 to determine the level of hazard and then establish a local mitigation program.

Expected damage for different building types can be estimated by generalizing experience from past earthquakes and applying it to future hypothetical events.

Figure 13.

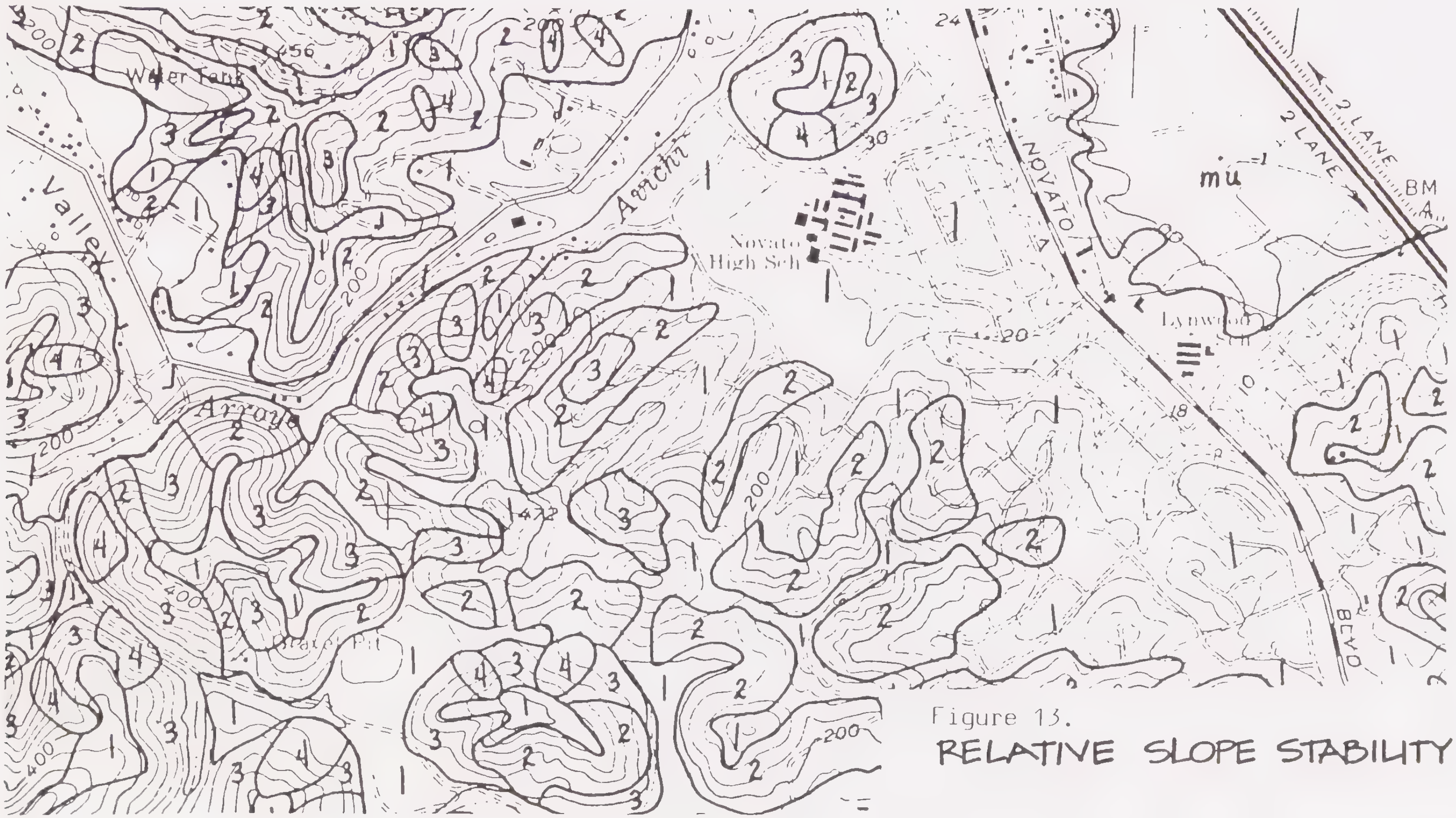



Figure 13.
RELATIVE SLOPE STABILITY

The Association of Bay Area Governments has developed generalized information as a damage ratio or damage factor for each intensity level for different types of buildings (see Table 5). This factor is defined as the cost of repairing a building divided by the cost of replacing that building. Curves of these loss percentages, or damage ratios, are shown below for seven typical building types. The curves can provide a simple means of gauging the relative performance of buildings during earthquakes. Following is a general definition of different types of buildings.

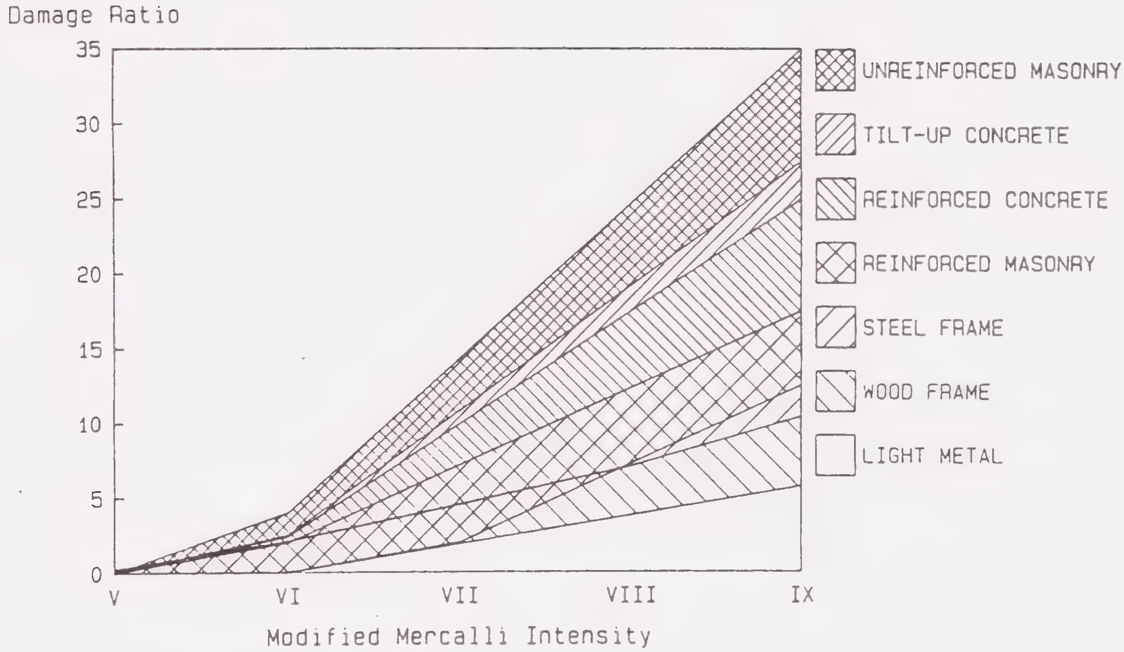
1) *Wood Frame*: Wood frame buildings are usually low, of one to four stories. Most tend to have wood stud bearing and non-bearing walls. For new construction, floors are generally plywood topped with the finish flooring. Foundations are generally concrete or masonry. However, concrete or masonry may not be reinforced in older buildings. Chimneys may be reinforced or unreinforced masonry, or prefabricated sheet metal, and either tied or not tied to the wood structure. Uses include single and multi-family housing, smaller commercial buildings, motels and older industrial buildings.

2) *Mobile Home*: A mobile home is a factory-built dwelling either of light weight metal construction or a combination of wood frame structure erected on a steel frame chassis, with siding of wood, aluminum, or fiberglass.

3) *Light Metal*: Light metal structures contain light metal stud walls with metal sheathing or a stucco finish. Floors tend to be concrete or plywood on steel joists. Interior walls and ceilings tend to be sheetrock. Roofing can be of a varying material, including corrugated metal. Uses include gas service stations, warehouses, industrial buildings, agricultural buildings, and small shops.

4) *Reinforced Masonry*: Reinforced masonry construction has concrete block or brick as its primary material. The structural system generally consists of masonry bearing and shear walls, with wood floors and roofs, although metal deck floors and roofs are used. Inside partitions may be wood or light metal stud walls. These buildings are generally limited to about four stories in height.

## Table 5. Expected Damage to Selected Building Types




Source: Building Stock and Earthquake Losses: The San Francisco Bay Area Example. Association of Bay Area Governments, May 1986, p. 17

5) *Unreinforced Masonry (URM)*: Although unreinforced masonry buildings are usually adobe, stone or brick, concrete block structures with either no grouting, no steel reinforcing, or both are in existence. Floors, roofs, and internal partitions in these bearing wall buildings are usually of wood. URM was usually constructed in an era when reinforcing was generally not used, or when anchorage to floors and roof were missing, or when low strength lime mortar was used. Construction of reinforced masonry became common sometime between 1933 and 1955, depending on local codes and quality of code enforcement. Many older masonry buildings have performed excellently in strong earthquakes. They require detailed review to verify their adequacy. Uses are commercial, housing, and industrial.

6) *Steel Frame*: Steel beams and columns with either simple, semirigid connections are commonly used with concrete over metal deck, or commonly in older buildings, concrete slabs for floor and roof. The steel frame may be combined with masonry walls (unreinforced in older buildings), cast in place concrete walls, or light-weight pre-cast concrete curtain walls.

   Modern high-rise office buildings use a moment-resisting frame and concrete over steel decking for floors. Low-rise buildings may have wood floors and roofs.

7) *Reinforced Concrete:* Concrete buildings are constructed in a variety of ways. Cast-in-place concrete frame buildings with steel reinforcement usually have concrete beams and columns. A building may have reinforced cast-in-place concrete walls, nonstructural cladding, or curtain walls. In these structures, the floors may be steel decking or concrete slabs. If concrete, they may also be precast. Older concrete buildings often are cast-in-place bearing wall design.

8) *Tilt-up Concrete*: Tilt-up concrete is a construction method using walls of reinforced concrete that are cast flat and tilted up into place. These wall elements may be interconnected with pilasters, or may be separated. The detailing of the anchors and the diaphragm, and the interconnections of the walls can vary widely, yet this detailing has a major effect on earthquake performance.

The Association of Bay Area Governments has mapped earthquake hazards for various types of buildings. Figures 14, 15 and 16 show cumulative damage potential from earthquake ground shaking for tilt-up concrete, concrete and steel, and wood frame buildings. The extent of various types of buildings by land use category in Marin County and other Bay Area counties is shown in Table 6.

Statistically, unreinforced masonry buildings are the type of structure most susceptible to damage. Recently, the State (through SB 547 as described earlier) mandated that each local government in California identify all unreinforced masonry buildings in its jurisdiction and establish a local program for mitigation of identified potentially hazardous buildings. There are an estimated 50,000 unreinforced masonry buildings in the State with approximately 5,000 unreinforced masonry buildings in the nine-county Bay Area, and over 2,100 located in the City of San Francisco. Most cities in Marin County are in the process of undertaking a study to identify potential buildings subject to the SB 547 requirements. The Seismic Safety Commission has produced guidebooks for identifying potential buildings and developing a mitigation program. Below is an estimated total of buildings that may be affected in the various Marin County jurisdictions. Most buildings are located in the downtown areas of Marin's cities.

**Table 6. Estimated Number of Unreinforced Masonry Buildings in Marin County**

| Jurisdiction | Estimated # of Buildings |
|---|---|
| Sausalito | 11 |
| Mill Valley | 25 or less |
| Corte Madera | 0 |
| Ross | 1 |
| Tiburon | up to 5 |
| Larkspur | 3-4 |
| San Anselmo | 20-30 |
| Fairfax | 3-30 |
| San Rafael | 100 |
| Novato | 13 |
| West Marin (Point Reyes Station) | 1 |
| Total | 151 - 219 |

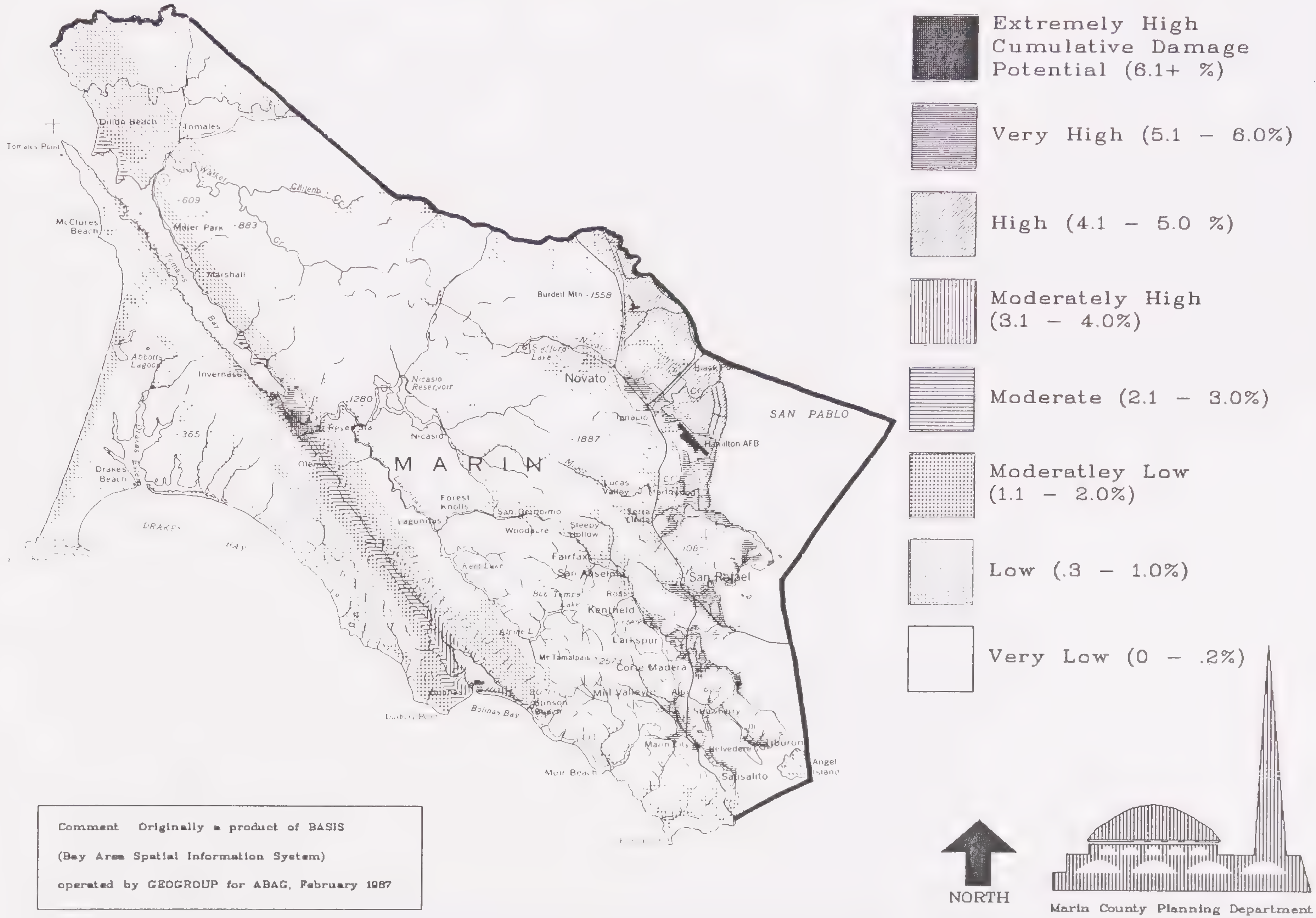
Although unreinforced masonry buildings have become the symbol for hazardous buildings, they are by no means the only potential problem. Many seismic safety planners expect additional legislation to be added requiring similar mitigation for tilt-up concrete and reinforced concrete buildings.

In California counties, the Uniform Building Code, specifically its sections relating to earthquakes, functions as the basic set of minimum requirements for seismic shaking and ground displacement resistance in all new structures. The Field Act, adopted after the Long Beach earthquake of 1933, consists of very detailed and rigorous specifications for construction materials, minimum earthquake loads and provisions for supervision of construction of all public school buildings to these standards.

The predominant sources of earthquake damage expected in the uplands of Marin County are from landslides and fires triggered by the shaking. Because many streets in the hills of central and southeastern Marin County traverse upslope landslide deposits, and streets are the usually routes of underground utility pipes, it should be expected that a great earthquake generated in the north Bay Area will result in the disruption of some transportation routes and the rupturing of water, gas, and sewer lines as a result of earthquake-induced landslides.

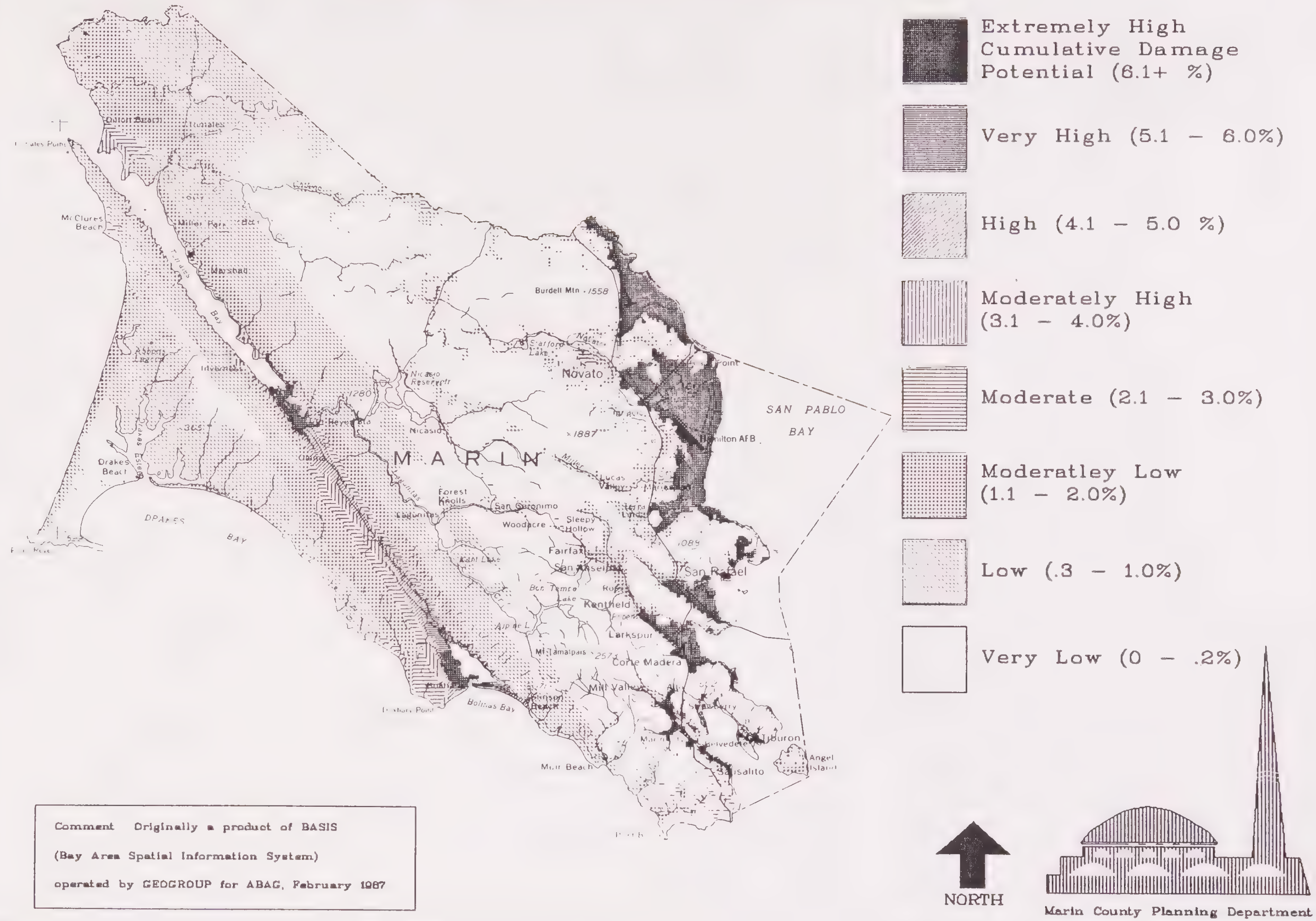
Fire is also likely to be a destructive by-product of a great earthquake in this area, perhaps the worst by-product if the earthquake occurs during the dry season. Fire was the most significant source of property damage in the San Francisco 1906 earthquake. It should be expected that many fires would be ignited in Marin County from a major or great earthquake. These fires would probably be caused by gas appliance pilot flames which would ignite the gas escaping from ruptured pipes, especially from top-heavy water heaters which could come loose from their pipe connections.

**Figure 14. Cumulative Damage Potential from Earthquake Ground Shaking for Tilt-Up Concrete Buildings**



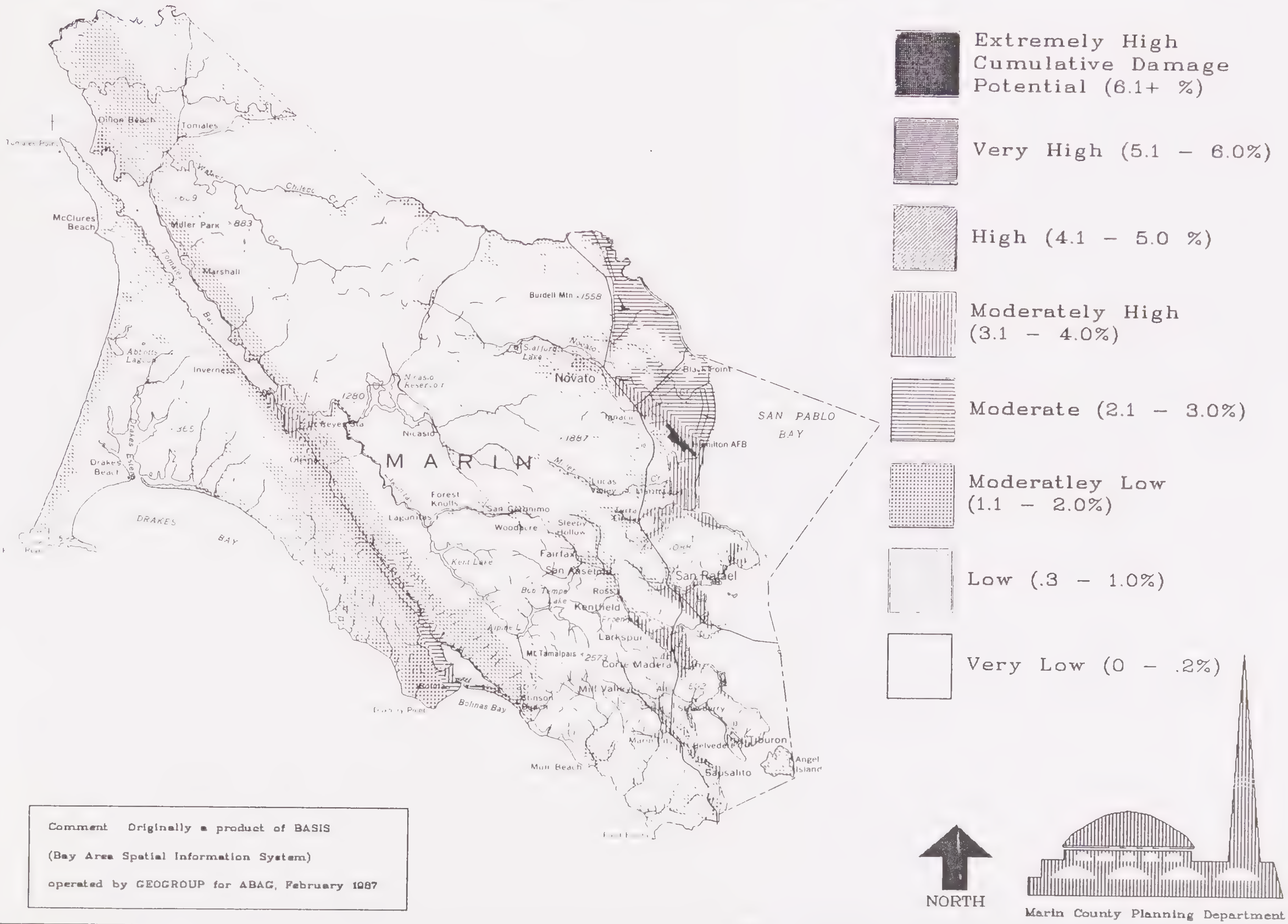

Comment Originally a product of BASIS (Bay Area Spatial Information System) operated by GEOGROUP for ABAG, February 1987

**Figure 15. Cumulative Damage Potential from Earthquake Ground Shaking for Concrete and Steel Buildings**




Comment Originally a product of BASIS (Bay Area Spatial Information System) operated by GEOGROUP for ABAG, February 1987

**Figure 16. Cumulative Damage Potential from Earthquake Ground Shaking for Wood Frame Dwellings**

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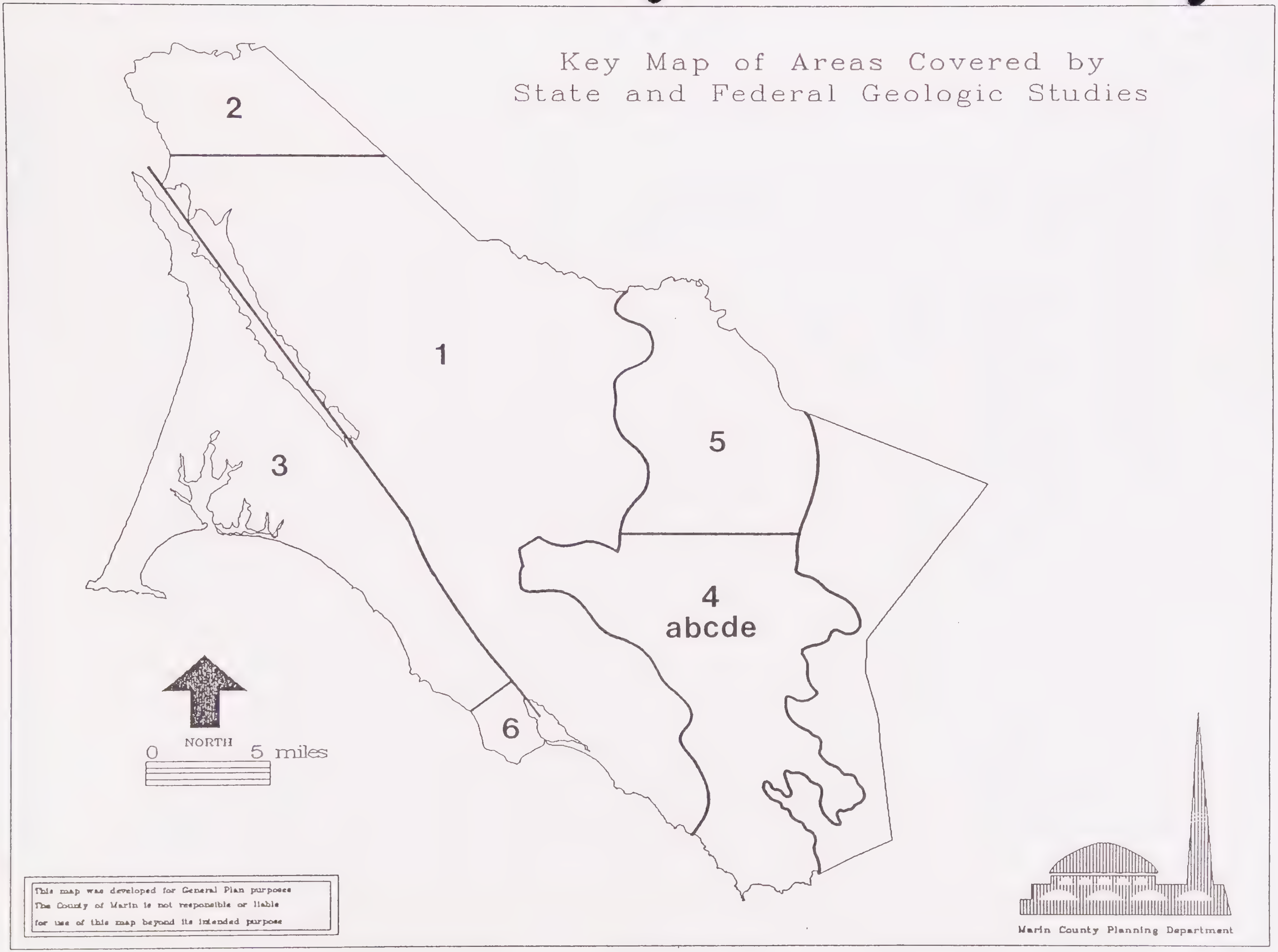
# APPENDIX 1. MAP AND INDEX OF AREAS COVERED BY STATE AND FEDERAL GEOLOGIC STUDIES


Key Map of Areas Covered by
State and Federal Geologic Studies
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This map was developed for General Plan purposes
The County of Marin is not responsible or liable
for use of this map beyond its intended purpose
Marin County Planning Department

**INDEX TO KEY MAP OF AREAS IN MARIN COVERED BY STATE AND FEDERAL GEOLOGIC STUDIES**


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    a. Plate 1a: Geology of the San Geronimo Valley area, Marin County, California; by Theodore C. Smith, scale 1:12,000.

    b. Plate 1b: Geology of the Upper Ross Valley and the western part of the San Rafael area, Marin County, California; by Theodore C. Smith, Salem J. Rice, and Rudolph G. Strand, scale 1:12,000.

    c. Plate 1c: Geology of the eastern part of the San Rafael area, Marin County, California by Salem J. Rice, Rudolph G. Strand, and Theodore C. Smith, scale 1:12,000.

d. Plate 1d: Geology of the lower Ross Valley, Corte Madera, Homestead Valley, Tamalpais Valley, Tennessee Valley and adjacent areas, Marin County, California, compiled by Salem J. Rice and Theodore C. Smith, scale 1:12,000.

e. Plate 1e: Geology of the Tiburon Peninsula, Sausalito, and Adjacent Areas, Marin County, California, compiled by Salem J. Rice and Theodore C. Smith, scale 1:12,000.

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# APPENDIX 3. PERSONS AND AGENCIES CONSULTED

1. Jack Baker, Marin County Department of Public Works

2. Bay Area Regional Earthquake Preparedness Project

3. California Division of Mines and Geology

4. Bill Doyle, Marin County Department of Emergency Services

5. Scott Hochstrasser, Environmental Coordinator, Marin County Planning Department

6. Jeanne Perkins, Association of Bay Area Governments

# APPENDIX 4. GLOSSARY OF TERMS

**Acceptable Level of Risk:** Acceptable level of risk from the point of view of the public agency is that level of risk at which no governmental response is considered necessary.

**Active Faults:** Active faults are faults which show evidence of any or all of the following: (1) topographic or physiographic expressions suggestive of geologically young fault movements; (2) fault creep; or (3) records of surface rupture within or adjacent to the study area in historic time.

**Alluvium**: A general term for the sediments laid down in river beds, floodplains, lakes, fans at the foot of the mountain slopes, and estuaries during relatively recent geologic times.

**Amplification:** The increase in earthquake ground motion that may occur to the principal components of seismic waves as they enter and pass through different earth materials.

**Amplitude:** One-half the elevation of the crest of a wave or ripple above the adjacent troughs.

**Colluvium**: Rock, organic debris, and soil accumulated at the foot of a slope.

**Differential Settlement**: Uneven settlement that occurs with time or during earthquake shaking in poorly consolidated granular soils adjacent to bedrock. Loss of strength or the loss of water and sand through liquefaction often does not occur evenly over broad areas. Thus the ground settles different amounts in adjacent spots. Can be very destructive to buildings.

**Displacement:** The dislocation of one side of a fault relative to the other side resulting from fault movement.

**Debris Avalanche Landslides:** Although similar to debris flows, debris avalanches move more rapidly, with single episodes that last only seconds. They occur suddenly in over-saturated sandy or silty soils, such as those derived from the sandstone and shale unit. The soils tend to liquefy and flow rapidly downslope at speeds of up to 20 miles per hour. Because of their highly fluid nature, debris avalanches travel long distances and are controlled by drainage channels and canyons. Therefore, the mouths of canyons downslope of sandstone ridges are highly vulnerable to such avalanches.

Studies by the U. S. Geological Survey in 1985 and the California Division of Mines and Geology in 1984 indicate that the intensity of rainfall influences the occurrence of debris avalanches. When 10 to 15 inches of rainfall has accumulated in the soil and subsequent rainfall occurs at a rate of greater than one-half inch per hour for four hours, or greater than four inches in 10 hours, debris avalanches are likely to occur. Debris avalanche landslides are probably the most hazardous type of landslide affecting the Marin County planning area.

**Debris Flow Landslides:** Debris flows are associated with sandy soils and move more rapidly downslope that earthflows, usually during a single episode lasting a few minutes or hours. Debris flows usually occur in soils derived from the sandstone and shale bedrock unit.

**Earthflow**: A landslide that occurs in clayey soils and moves slowly downslope at a velocity of a few meters or less per day. A slow flow of earth lubricated with water, an earthflow may be discriminated from an earth slump by reason of its greater mobility.

**Earthquake**: Perceptible trembling to violent shaking of the ground, produced by sudden displacement of rocks below and at the earth's surface.

**Epicenter**: The geographical location of the point on the surface of the earth that is vertically above the earthquake focus.

**Expansive Soils**: Soils that have a high clay content tend to be expansive. In other words, the clay tends to swell with increased moisture content and contract during dry spells. These volumetric changes with seasonal variations in moisture content can disrupt shallow foundations and pavements. On slopes, the annual swelling and shrinking of expansive soils causes the soil to migrate downslope at rates of a fraction of an inch per year. This downslope movement, known as soil creep, can disrupt foundations and utilities. Expansive and creeping soils should be identified prior to construction so that engineering measures can be implemented to minimize potential damage to structures.

**Focal Depth:** Depth of an earthquake focus below the ground surface.

**Focus**: The origin point of the elastic waves of an earthquake.

**Free Face**: A sloping surface exposed to air or water such that there is little or no resistance to lateral movement of earth materials.

**Ground Failure**: A situation in which the ground does not hold together such as landsliding, mud flows, and liquefaction.

**Ground Lurching**: Undulating waves in soft saturated ground that may or may not remain after the earthquake.

**Ground Strength**: The limiting stress that ground can withstand without failing by rupture or continuous flow.

**Inactive Faults**: The most recent epoch of geologic time, extending from 10,000 years ago to the present time.

**Intensity**: A non-linear measure of earthquake size at a particular place as determined by its effect on persons, structures, and earth materials. The principal scale used in the United States today is the Modified Mercalli, 1956 version. Intensity is a measure of effects as contrasted with magnitude which is a measure of energy.

**Landslide**: The downslope movement of soil and rock material en masse under the influence of gravity. Several varieties of landslide are a major geologic hazard to any works of man constructed on, adjacent to, upslope of, or in the downslope path of a landslide. The principal conditions that affect slope stability and the formation of landslides are: decomposition of the earth materials underlying the slope, slope steepness, the concentration of surface and ground water, earthquakes, and human activity. Human activity that may cause landslides include over-steeping cut-slopes, improper placement of fill on slopes, concentrating surface runoff, or injecting water into the ground. The most common landslides affecting Marin County include earthflows, debris flows and debris avalanches, all of which are restricted to soil and loose rock over bedrock. Some bedrock block landslides, which are masses of bedrock that have moved downslope, also affect the County.

**Liquefaction**: A process by which a water-saturated sand loses coherence when shaken. The sand grains collapse into intergranular voids. The collapse induces an increase in pore pressure and loss of strength. This loss of strength leads to a quicksand condition in which objects can either sink or float depending on their density.

**Magnitude**: A measure of the energy released in an earthquake is the rating of a given earthquake is defined as the logarithm of the maximum amplitude on a seismogram written by an instrument of specified standard type at a distance of 62 miles from the epicenter. It is a measure of the energy released in an earthquake. The zero of the scale is fixed arbitrarily to fit the smallest recorded earthquakes. The scale is open ended but the largest known earthquake magnitudes are near 8.75. Because the scale is logarithmic, every upward step of one magnitude unit means a 32 fold increase in energy release. Thus, a magnitude 7 earthquake releases 32 times as much energy as a magnitude 6 earthquake. Magnitude is not the same as intensity.

**Plate Tectonics:** An earth model in which a small number (10-25) of large, broad, thick plates of the earth's surface believed to "float" on an underlayer and move more or less independently, grinding against each other like ice floes in a river. The plates are propelled from the rear by sea-floor spreading. The continents form part of the plates and move with them like blocks of wood in an ice floe.

**Sediment:** Solid material settled from suspension in a liquid.

**Seismic:** Pertaining to an earthquake or earth vibration, including one which is artificially induced.

**Seiche**: A wave generated in an enclosed body of water.

**Seismic Velocity:** The rate of propagation of an elastic wave. The velocity depends upon the type of wave and the elastic properties and density of the earth material through which it travels.

**Subsidence**: Settlement that may occur over a broad area if soils density with time or as a result of ground water withdrawal. Settlement may occur in the colluvium or alluvium soils resulting in damage to structures, utilities and roadways.

**Tectonics:** A study of the origin, relations, and evolution of structural features of the earth's crust, such as folding and faulting of the rocks.

**Tsunami:** A sea wave produced by any large-scale, short-duration disturbance of the ocean floor, principally by a shallow submarine earthquake. Tsunamis are characterized by great speed and may cause considerable damage along an exposed coast thousands of miles from the source.

**Water Table**: The upper surface of a zone of water saturation within the ground.